HONORABLE ROGER S. ROGOFF

SUPERIOR COURT OF WASHINGTON FOR KING COUNTY

RYAN M. PSZONKA, et al., Plaintiffs, v. SNOHOMISH COUNTY, et al., Defendants.	No. 14-2-18401-8 SEA **<u>PRELIMINARY</u>** EXPERT REPORT OF DR. J. DAVID ROGERS, Ph.D., P.E., P.G., C.E.G., C.HG. DR. MARVIN R. PYLES, Ph.D., P.E. DR. JONATHAN D. BRAY, Ph.D., P.E., NAE DR. ARNE SKAUGSET, Ph.D., RPF DR. RUNE STORESUND, D.Eng., P.E., G.E.
TIM WARD, et al. Plaintiffs, v. SNOHOMISH COUNTY, et al., Defendants.	
GREGORY REGELBRUGGE, et al., Plaintiffs v. STATE OF WASHINGTON, et al., Defendants	

Executive Summary

The SR 530 Landslide of March 22, 2014 was a tragedy of unparalleled proportions in this country. Nearly the entire long-term average annual loss of life from landslides in the continental United States occurred in this one event in the State of Washington for 2014. A few facts are not in question. The landslide was a deep seated landslide with an elevation difference from crest to toe of just over 600 feet, and portions of the slide mass traveled to a point just over a mile from the scarp. This report is the first of what will be a series of reports that will arise out of an effort to fully understand the causes of the landslide. It is a joint report prepared by an expert team assembled by the Attorney General of the State of Washington. This joint report is a preliminary document in which we review the hypotheses either directly listed or implied in the complaints regarding the proximate causes of the SR 530 Landslide of March 22, 2014.

Hypotheses that we discuss herein include:

- Hypothesis 1 – Clear-cut timber harvesting will result in increased through-fall that results in a direct increase in groundwater;
- Hypothesis 2 – The SR 530 Landslide failure mechanism was driven by unconfined gravitational seepage;
- Hypothesis 3 – Erosion by the Stillaguamish river at the toe of the slope destabilized the slope and resulted in the SR530 landslide;
- Hypothesis 4 – Construction of settling ponds near the toe of the slope for the purpose of reducing sediment input to the river to benefit fisheries destabilized the slope; and
- Hypothesis 5 – Stability analysis done before the SR 530 Landslide with subsurface information available at the time demonstrated within the standard of practice that the landslide was going to occur and endanger the Steelhead Haven neighborhood.

This must be considered a preliminary document because, in the opinion of the authors, we believe there is insufficient factual information available at the present time to offer an informed opinion. It is not possible to evaluate the March 22, 2014 SR 530 Landslide and to form defensible opinions regarding its causative mechanisms and to identify potentially important contributing factors to its instability without subsurface investigations and monitoring that help define the landslide geometry, the engineering properties of the key geologic units, and the groundwater conditions within and below the landslide.

A subsurface exploration program coupled with a geotechnical testing program will provide factual information on which to base an informed opinion. While it is not our desire to slow the legal process in this case, we believe we have an obligation to maintain the standards of our professional practice in civil engineering and forestry.

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Nature of Involvement

The members of the expert team that prepared this report were retained by the State of Washington's State Attorney General to form opinions in relation to the following questions with respect to the SR530 Landslide that occurred on March 22, 2014:

1. The causation of the SR530 landslide;
2. The predictability of the SR530 landslide in the time frame of pertinent DNR FPA approvals;
3. The predictability of the runout of the SR 530 Landslide; and
4. The impact of pertinent DNR approved timber harvests on the Whitman Bench with regard to the causation of the SR 530 Landslide.

This report is preliminary due to the lack of critical minimum factual information about the landslide, which is proposed to be obtained via a site-specific geotechnical exploration and laboratory testing program. At the time the expert team was assembled in September, 2014, the landslide site was simply too unsafe to conduct more than a cursory visual observation of the area and the surface of the slide scar and the debris field. As a work assignment, the team was also asked to develop a field exploration program plan that encompasses the forest hydrology of the forest stands and recent clear-cut harvest units on the Whitman Bench, and the subsurface conditions below the ground surface of the Whitman Bench and within the landslide scar that would provide factual data for use in addressing the four items listed above. In addition to the field exploration program, it was recognized that laboratory testing for purposes of characterizing the geotechnical properties of the materials involved in the SR 530 Landslide would also be required. The finalization of the subsurface exploration plan and laboratory testing plan is pending.

Credentials and Compensation

Dr. J. David Rogers, Ph.D., P.E., P.G., C.E.G., C.HG. holds the Karl F. Hasselmann Chair in Geological Engineering in the Department of Geosciences and Geological and Petroleum Engineering at the Missouri University of Science & Technology. He has 35 years of experience in evaluating the stability of natural slopes, embankments, stream channels, highways and hydraulic structures. Between 1979 and 2001, he managed over 500 projects in the western United States, Hawaii, Taiwan, the Philippines and the Middle East. He has served as principal investigator for scientific research funded by the National Science Foundation, U.S. Geological Survey, Federal Highway Administration, Department of Defense and the California and Missouri Departments of Transportation. Much of Dr. Roger's research over the past 15 years has focused on regional landslide hazard mapping, in the United States, Ethiopia, Pakistan, and Nepal. He has also studied long-runout landslides in California, Colorado, Alaska, Wyoming, Montana, Washington, Pakistan, and Papua New Guinea. Dr. Rogers has served on a number of panels, including the National Academies panel on 'Levees and the National Flood Insurance Program,' the Technical Advisory Committee on Regional Geologic Studies and Slope Stability Modeling for the California Geological Survey, and the Building Codes and Dam Safety Committees of the Association of Environmental & Engineering Geologists. Dr. Rogers' hourly rates are $275/hr for straight time; $350/hr for deposition and trial testimony preparation; and $500/hr for deposition and trial testimony, without any minimum number of hours charged.

Dr. Marvin Pyles, Ph.D, P.E., F.ASCE, is a Professor Emeritus of Forest Engineering at Oregon State University. He is a registered Professional Engineer in Washington, Oregon and California, and specializes in Geotechnical Engineering and the regulation of Forest Practices with respect to landslide and other erosional processes. Dr. Pyles rate for normal consulting is $200 per hour plus expenses, and for depositions and court testimony, $400 per hour plus expenses.

Professor Jonathan D. Bray, Ph.D., P.E., NAE is a registered professional civil engineer and professor of civil and environmental engineering at the University of California, Berkeley (see attached CV). Dr. Bray is a professor of geotechnical engineer with expertise in subject matters such as slope stability, soil characterization, numerical analysis, earthquake engineering, and post-event reconnaissance.   Dr. Bray's consulting fee for providing engineering services on a project involved in litigation is $300.00 an hour plus expenses and $450.00 an hour plus expenses for work involved in preparation for and performance of deposition or testimony.

Dr. Arne Skaugset, Ph.D., R.P.F., is an expert on forest management and forest engineering; Hydrologic impact of timber practice; landslide-prone land management in the forest environment; precipitation data collection and analysis; landslide hazard analysis, identification and mitigation; landslide triggers and rainfall intensity. Dr. Skaugset's consulting fee of providing technical expertise is $250 an hour plus expenses. That fee is $500 an hour for depositions and testimony.

Dr. Rune Storesund is a licensed civil engineer with 15 years of civil engineering experience and 10 years of forensic engineering experience in the areas of geotechnical, water resource, and environmental engineering. He provides civil forensics support for pre-trial review, engineering standard of care, document/data review and synthesis, engineering contract review, forensic investigations and analyses, failure mode analysis, legal visual aids & animations, and expert witness services. He also has expertise on survey methods including Total Station, RTK GPS, and LiDAR. He has a Doctorate of Engineering in Civil Systems and a Masters in Geotechnical Engineering from UC Berkeley. Dr. Storesund is the Executive Director of UC Berkeley's Center for Catastrophic Risk Management, a group of academic researchers and practitioners who recognize the need for interdisciplinary solutions to avoid and mitigate tragic events. This group of internationally recognized experts in the fields of engineering, social science, medicine, public health, public policy, and law was formed following the tragic consequences of Hurricane Katrina to formulate ways for researchers and experts to share their lifesaving knowledge and experience with industry and government. Dr. Storesund serves as a technical reviewer for the National Academy of Forensic Engineers (NAFE). In the past 10 years, he has participated in the following forensic investigation: Mississippi River Gulf Outlet Wave-Induced Erosion, St. Bernard Parish, Louisiana; Investigation of the Greater New Orleans Area Flood Defense System Failure, New Orleans, Louisiana ; Upper Jones Tract Levee Failure, San Joaquin County, California; East Bank Industrial Area (Lower 9th Ward), New Orleans, Louisiana; PNG Landslide, Papua New Guinea (underlined indicates expert witness-related cases). Dr. Storesund is compensated at a rate of $175.00 per hour for engineering consultations, $262.50 per hour for testimony preparation, and $350 per hour for expert testimony/depositions, plus incurred expenses.

Available Information

Significant quantities of information have become available to the expert team since September 2014. As the discovery process continues, and as our proposed field exploration, laboratory testing, and monitoring program are implemented, more data will become available. Available information has been categorized and briefly discussed below.

Aerial Imagery (1947-2014)

Aerial imagery provides a snapshot of site conditions (such as river alignment, ground cover, etc.) at the time the photograph was taken. Historic aerial images (to date) cover the period 1947 to 2014. A catalog of available images is presented in Appendix A – Aerial Image Catalog.

Aerial LiDAR Data Sets (2003-2014)

The following Digital Elevation Models (DEMS) based on Aerial Light Detection and Ranging (LiDAR) data sets were made available to the expert team:

- Mt. Higgins Meadow Mtn (flown in 2003) <available from: http://core2.gsfc.nasa.gov/lidar/terrapoint/darrington/Mt_Higgins_Meadow_Mtn.tar.gz>
- Snohomish County Dataset (2005-2006) <available from: http://pugetsoundlidar.ess.washington.edu/lidardata/restricted/nonpslc/snohomish05-06/index.html>;
- 2013 Tulalip LiDAR project (2013) <available from: http://pugetsoundlidar.ess.washington.edu/lidardata/restricted/projects/2013tulalip.html#Oso>; and
- State of Washington Department of Transportation Oso Landslide/Stillaguamish River LiDAR(2014) <available from: http://pugetsoundlidar.ess.washington.edu/lidardata/restricted/nonpslc/oso2014/>.

LiDAR data provides the ability to generate to-scale three-dimensional (3D) representations, which greatly enhances the resolution and visualizations of complex topographies (when compared to conventional plan-based topographic maps).

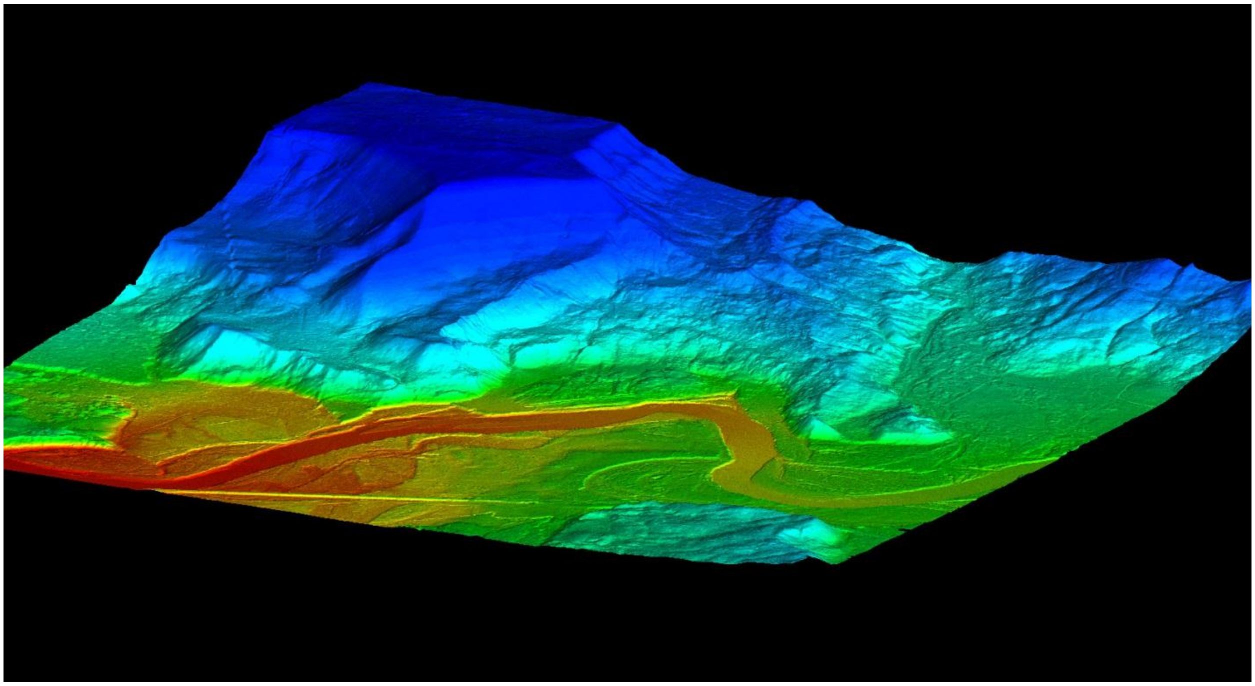

Figure 1: Aerial oblique view of SR 530 Landslide site based on 2003 Aerial LiDAR data.

Existing Reports/Documents

Numerous reports have been made available to the expert team. These include:

a. William D. Shannon and Associates, 1952, Report on Slide on North Fork Stillaguamish River, near Hazel Washington.
b. Gerald W. Thorsen, field visit November 28, 1969 [figures dated January 27, 1970], Memorandum on the Landslide of January 1967 which diverted the North Fork Stillaguamish River near Hazel.
c. Lee Benda, Gerald Thorsen, and Steve Bernath, October 30, 1988 [revised 11/23/88], Report of the I.D. Team investigation of the Hazel Landslide on the North Fork of the Stillaguamish River (FPA 19-09420).
d. Daniel J. Miller, 1995, Coupling GIS with Physical Models to Assess Deep-Seated Landslides Hazards. Environmental & Engineering Geoscience, Vol, I, No. 3 Fall 1995.
e. Dan Miller and Joan Sias, no date on the document [listed with a date of 1997 in reference lists], Environmental Factors Affecting the Hazel Landslide, Level 2 Watershed Analysis, Hazel , Washington. M2 Environmental Services.
f. Daniel J. Miller and Joan Sias, 1998, Deciphering large landslides: Linking hydrological, groundwater and slope stability models through GIS, Hydrological Processes, Vol. 12.
g. M2 Environmental Services [based on the page footers], 1999, Hazel/Gold Basin Landslides: Geomorphic Review Draft Report.
h. US Army Corps of Engineers, November 2000, Final Environmental Assessment: Stillaguamish River Ecosystem Restoration – Puget Sound and Adjacent Waters Authority.

i. US Army Corps of Engineers, October 2000, Final Feasibility Report: Stillaguamish River Ecosystem Restoration.
j. GeoEngineers, Inc., 4/26/01, Steelhead Haven Landslide Remediation Feasibility Study.
k. Joe D. Dragovich, et.al. 2003, Geologic Map of the Mount Higgins 7.5-minute Quadrangle, Skagit and Snohomish Counties, Washington, Washington Department of Geology and Earth Resources.
l. Geotechnical Extreme Events Reconnaissance, July 22, 2014, The 22 March 2014 Oso Landslide, Snohomish County, Washington.
m. Ralph Haugerud, 2014, Preliminary Interpretation of Pre-2014 Landslide Deposits in the Vicinity of Oso, Washington. USGS Open-File Report 2014-1065.
n. Kate Allstadt, 26 March 2014, Seismic Signals generated by the Oso Landslide, Pacific Northwest Seismic Network.
o. Gerstel, Wendy J. and Thomas C. Badger, 2014, Reconnaissance mapping and characterization of landslides along state route 530 between mileposts 35 and 41 Snohomish County, Washington.
p. Everett, Aaron and Sue Casey. "Department of Natural Resources' Investigative Review of Forest Practices Activities in the Vicinity of the SR 530 Landslide," December 8, 2014.
q. Allstadt, K. (2015). Interactive comment on "Seismology of the Oso-Steelhead Landslide" by C. Hibert et al., Nat. Hazards Earth Sys. Sci. Discuss, 2, C3274-C3283.
r. Hibert, C., C. P. Stark, and G. Ekstrom (2014). Seismology of the Oso-Steelhead Landslide, Nat. Hazards Earth Sys. Sci. Discuss, 2, 7309-7327.
s. Iverson, R. M., D. L. George, K. Allstadt, M. E. Reid, B. D. Collins, J. W. Vallance, S. P. Schilling, J. W. Godt, C. M. Cannon, C. S. Magirl, R. L. Baum, and J. A. Coe (2015). Landslide mobility and hazard: implications of the 2014 Oso disaster, Earth and Planetary Science Letters, 412, 197-208.

Eyewitness Accounts

We have not received depositions to date of eyewitness accounts to the March 22, 2014 SR 530 Landslide event.

Historic Topographic Surveys

Historic topographical surveys that include the SR 530 Landslide area include United States Geological Survey (USGS) topographical maps with varying scales (1:24,000; 1:62,500; 1:100,000; 1:125,000; and 1:250,000) from 1901 through 1989. A map based on topographic surveys from the State of Washington Department of Game in October-December 1951 was presented in the Shannon Report (1). Additionally, a topographic map (with scale of 1 inch = 400 feet) was prepared by the State of Washington Department of Natural Resources, dated February 2, 1990) was available.

Precipitation Records

Local rainfall records were made available via the Western Regional Climate Center. The nearest measurement station is the Darrington Ranger Station (available from: http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?wa1992), which has a period of record from December 1, 1911 to December 31, 2014.

As discussed below in "Rainfall Monitoring Program," a site-specific network of tipping bucket rain gages was recently installed at the site of the SR 520 Landslide.

Streamflow Records

Historic stream discharge of the Stillaguamish River, downstream of the SR 530 Landslide, is available via the USGS National Water Information System. The nearest station with an extended period of record is the USGS Site 12167000, "North Fork of the Stillaguamish River near Arlington, WA," (2) which has daily discharge and gage height readings from August 1, 1928 through present.

Rainfall Monitoring Program

A network of 26 tipping bucket rain gages were installed in the vicinity of the Oso landslide to quantify the effect of the different aged forest canopies on precipitation through-fall delivered to the soil surface. The rain gages are installed in each of the three age classes of forest present in the vicinity of the slide scarp: 9-year old stand, 27-year old stand, and an 80+ year old stand. The forest in the 27-year old stand where the rain gages are installed was commercially thinned in 2009-2010. The rain gages are installed in three transects of eight gages each, in the three different aged forest stands (Figure 2). In addition there are two rain gages installed in a small clear-cut approximately 1½ miles north of the slide. The rain gages were installed and data collection began on November 20, 2014 and the last download available for data reduction is April 14, 2015.

Figure 2: Overview map of tipping bucket locations.

The average through-fall measured for each of the different aged forest stands and the clear-cut are shown in Table 1. The clear-cut, as expected, has recorded the most rainfall. The different age classes of forest all received roughly the same amount of through-fall. The through-fall for the 9- and 27-year old stands is virtually the same. The through-fall for the 80+ year old stand is numerically less than the other two.

Table 1: Summary of rainfall results by stand age

Stand Age	Total Ave. rainfall (in)	Range (Hi to low)
Clearcut	48.84	
9 years	39.65	49.48 – 29.30
27 years	38.78	47.25 – 31.50
80 years	34.10	43.83 – 24.47

The through-fall values for the different age class forest stands are averages calculated from the eight rain gages in each stand. There is high variability among the through-fall values for each stand. This variability is represented by the range in the through-fall values for each stand listed in the table and illustrated in Figure 3. There are only two rain-gages in the clear-cut and a complete record does not exist for either, thus a range in through-fall values is not presented for the clear-cut. In every forest stand, the variability in through-fall values between the rain-gages in a given stand is much greater than the variability among the different aged stands. Thus, for all practical purposes, no difference exists in through-fall between the three different aged stands.

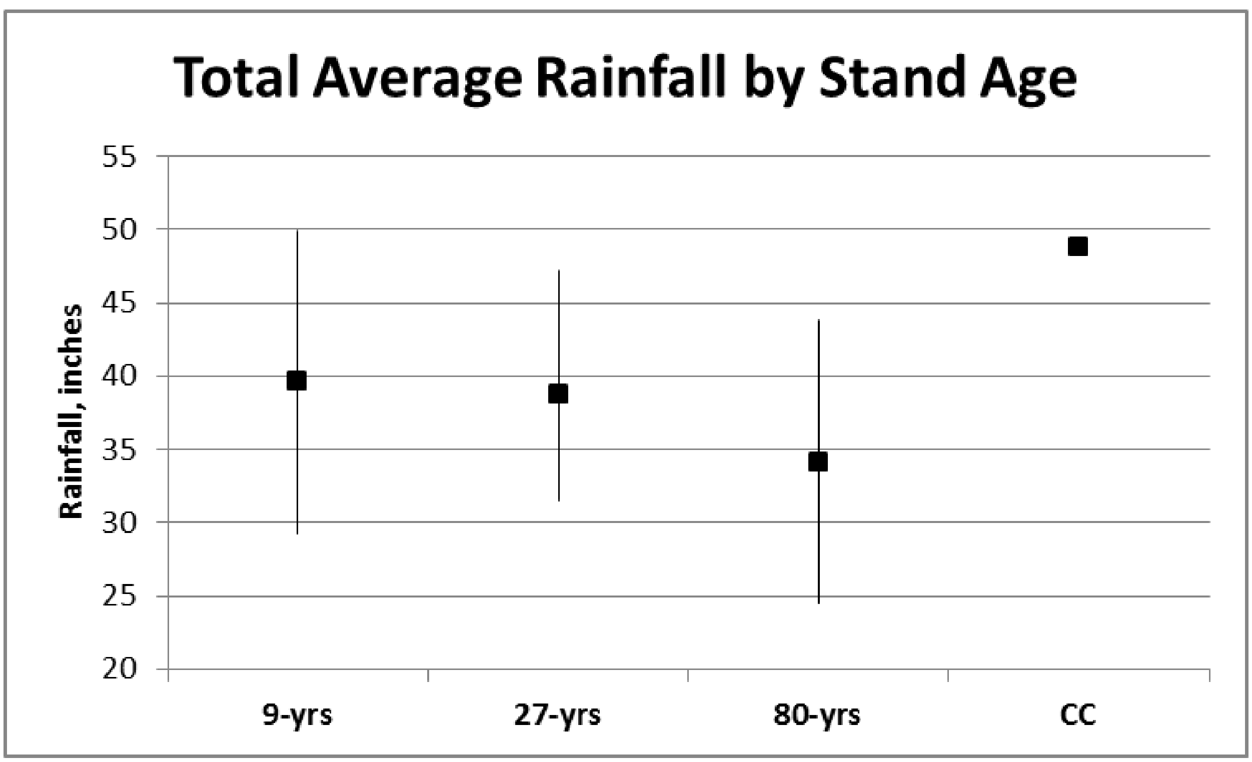

Figure 3: Total average rainfall by stand age.

WDOT Subsurface Exploration Program

A WSDOT boring advanced to a depth of 650 feet from the Whitman bench near the scarp of the SR 530 Landslide was performed in October 2014. USGS open file report 2015-1089 (3), which reports the geotechnical soil characterization of selected samples from the WSDOT boring became available in the week prior to issuing this report. Hence, only preliminary consideration of that information was made.

Site Context

Overview

The headwaters of the North Fork of the Stillaguamish River emanate from the vicinity of Finney Peak in Skagit County, approximately 10 miles north of Darrington. The upper water course flows south, then turns west through the hills that border the Snohomish-Skagit county line, where the discharge of Boulder River and Deer Creek join the mainstream. After flowing approximately 45 miles, it joins the South Fork of the Stillaguamish near Arlington. Upstream of its confluence the alluvial valley of the North Fork trends east-west, and varies in width, from just 300 feet (south of Rowan) to as much as a half mile.

The long-runout landslide of March 22, 2014 at Steelhead Haven, east of the village of Oso, occurred where the river took a sharp swing northward, excavating its channel at the base of an erosional escarpment approximately 600 feet high, capped by a terrace feature known as the Whitman Bench. The slide debris ran across the river valley where its base elevation was close to 300 feet above sea level. The debris crossed the river, absorbing its moisture, and engulfing the residential development of Steelhead Haven. The slide debris became fluidized and included hundreds of trees, which were carried across the alluvial valley in two flow lobes, one that spread to the southwest and another to the east and southeast, temporarily blocking the river channel. Most of the residential structures were shredded by the entrained tree trunks, with a few truss-diaphragm roofs and some recreational vehicles comprised the only semi-intact debris carried for any meaningful distance without disintegrating.

The undercut bank along the north side of the North Fork of the Stillaguamish River at this location had undergone periodic episodes of mass wasting impacting the channel with debris over the previous ~80 years, but none of these movements had been of a catastrophic nature, transporting debris for almost ¾ of a mile.

Geology & Stratigraphy

In the Puget Lowland Quaternary-age deposits (dating back to 2.4 million years before present) were deposited in drapery-like sheets up to 3,300 feet thick, testifying to no less than six glacial advances and interglacial periods. The Valley of the North Fork of the Stillaguamish has been the scene of considerable geologic deposition and denudation over the recent geologic past, especially, during the Wisconsin Glacial Stage of the last 70,000 years, when the Cordilleran Ice Sheet extended southerly, from what is now western Canada, into the Puget Lowland. Before the glacial advance, the natural drainages were similar to those in existence today and, the ancient Stillaguamish River flowed westward to the pre-Wisconsin oceanic shoreline. During the high sea stand of Isotope Level 5e, about 115,000 years before present (ybp), sea level actually rose 20 feet higher than at present. This higher sea stand allowed terrace gravels and alluvial sediments to be deposited at slightly higher elevations than at present (although few remnants of these were preserved). The Olympia age alluvial gravels were laid down by the ancient Stillaguamish, sometime between 70,000 and 30,000 ybp on a somewhat steeper gradient than currently exists, because sea level was considerably lower at that time.

Between 20,000 and 25,000 ybp there was a significant glacial advance that blanketed the Puget Lowland with ice, between zero and 5,000+ feet thick. The glacial mass thickened and widened itself as it advanced southward, blocking the channel draining the western side of the Cascades, as well as the Straits of Juan de Fuca. This has been termed the Frasier Glaciation, which occurred in two distinct stades, or glacial re-advances: the Evans Creek Stade, and the Vashon Stade. The maximum extent of this glaciation occurred during the Vashon Stade, approximately 15,000 ybp. At that time the ice reached an altitude of 3,300 feet above sea level (asl) at the Washington-British Columbia border, gradually thinning to about 1000 feet asl in the southern Puget Lowland. At the subject site, the maximum ice thickness likely reached 3,800 to 4,200 feet (accounting for the depth of the infilled valley and its being deflected downward by the weight of the ice). This glaciation sequence lasted about 10,000 years.

As the Puget Lobe pushed southward glaciofluvial and lacustrine sediment, in the form of boulders, cobbles, pebbles, sand, silt, and clay were deposited in the Vashon till, which blankets the Puget Sound area. The clasts comprising the Evans Creek and Vashon Tills were carried down from the Canadian Mountains, where the glacial advances sourced. During both stades, large glacial lakes were formed in the pre-glacial valleys dammed by the glacial mound filling the Puget Lowland. In the vicinity of the

North Fork of the Stillaguamish River the last sequence of glaciation, the Vashion Stade, retreated very quickly, depositing large quantities of gravel and cobbles on outwash plains, sands along the submerged slopes of the glacial lakes, and fine-grained silt, clay, and diamictons in the floors of those lakes. A schematic representation of this rapid depositional sequence is presented in Figure 4.

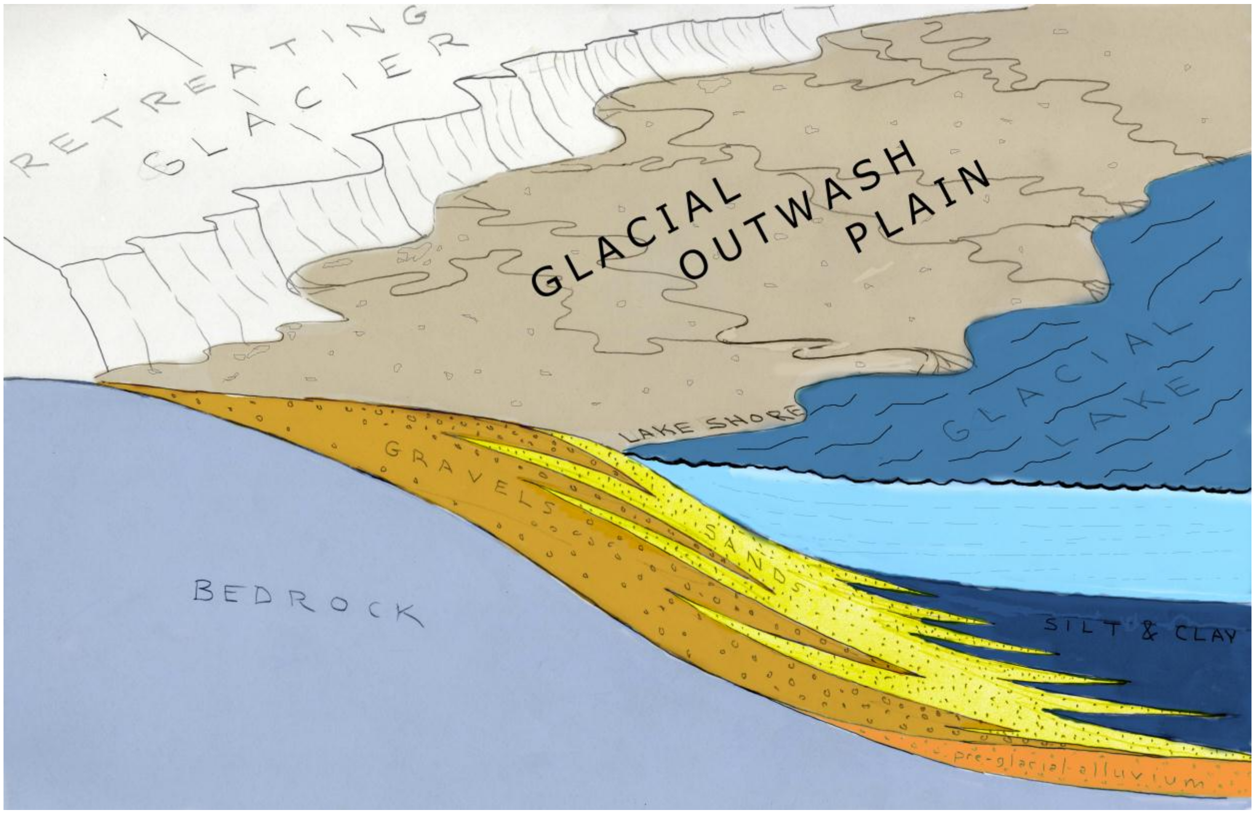

Figure 4: Schematic view of the rapid depositional sequence that occurred during the Vashon Stade advance and rapid retreat.

Figure 4 illustrates the manner by which cobbles, gravels, sands, silts, and clay sediments were more or less contemporaneously deposited during the rapid retreat of the Vashon Stade. Note how the various sediments inter-finger with one another, and are draped over the pre-existing topography. The pre-glacial Olympia alluvial sediments were locally preserved beneath this package of late Quaternary sediments, which reached a thickness of about 600 feet in vicinity of the 2014 Oso Landslide.

Recent geologic mapping by Dragovich et al.2003 (4) in their Geologic Map of the Mount Higgins Quadrangle for the Washington Department of Geology and Earth Resources identified a number of late Quaternary glacio-fluvial and alluvial units, as well as landslide complexes and lahars. The general stratigraphy of the quadrangle area is shown below left, while the Vashon Stade sequence dominating the site of the 2014 Oso landslide is sketched in Figure 5. These are schematic representations of the stratigraphic hierarchy of these sediments, not an accurate portrayal of their relative thickness, areal extent, or dip.

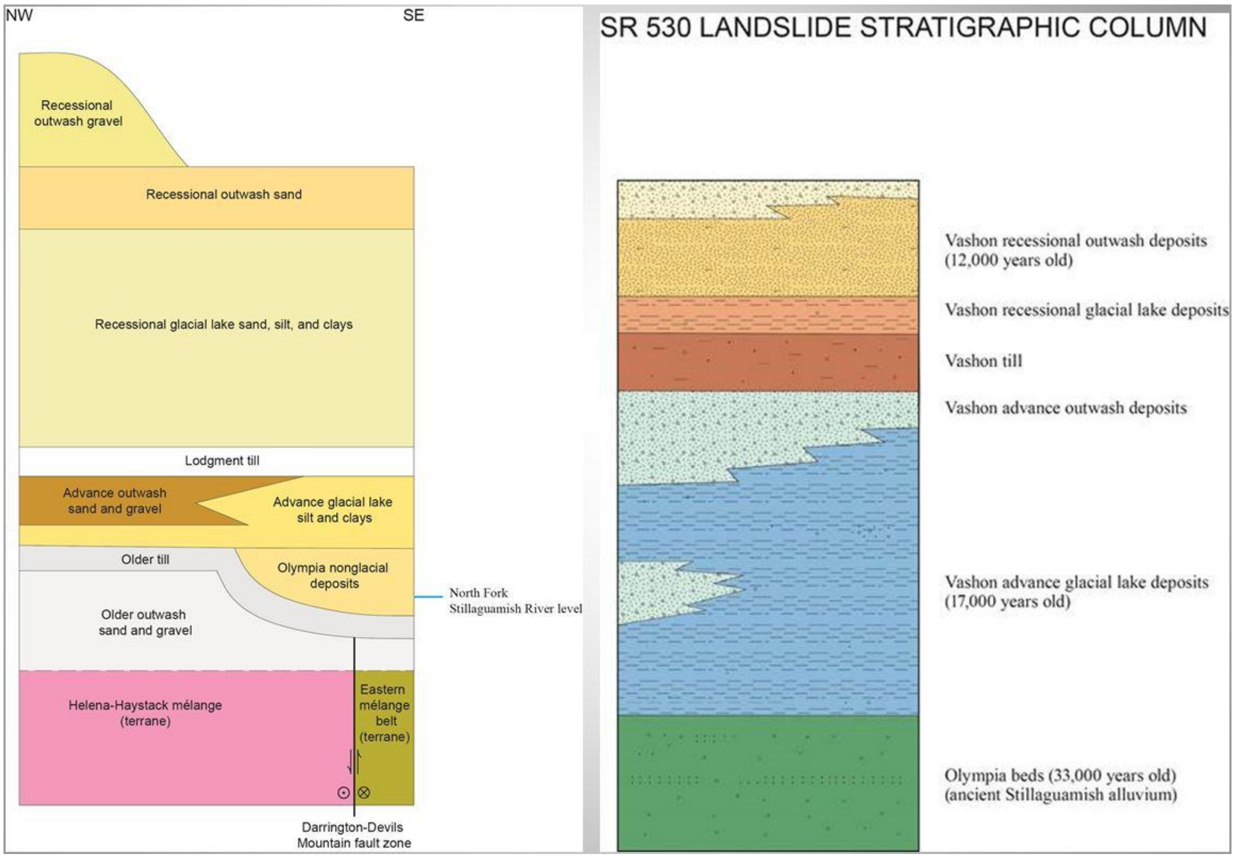

Figure 5: Generalized stratigraphic columns in the vicinity of the 2014 Oso Landslide (Dragovich).

Column at left in Figure 5 represents a schematic stratigraphic section of late Quaternary age map units included in the Geologic Map of the Mt Higgins Quadrangle in 2003. The schematic column at right of Figure 5 was prepared by DNR geologist Joe Dragovich, after the Oso Landslide of March 2014, to highlight those units he believes to comprise most of the recent landslide event, above the Olympia beds (shown in green). Note the glacial lake deposits emplaced during the Vashon Advance, about 17,000 ybp, which would have been subject to glacial loading. Also note the recessional outwash deposits of 12,000 ybp age, capping the Vashon Till. The Vashon recessional outwash gravels and sands form the prominent terrace known as the Whitman Bench, which lies at approximately 600 feet above the river in the vicinity of the SR 530 Landslide.

Prehistoric Landslide Events

There is ample geomorphic evidence of prehistoric landslides in the valley of the North Fork of the Stillaguamish River, pre-dating the exploration and settlement of the region in the early Nineteenth Century. The dense and pervasive tree cover of the western Cascades precluded the accurate preparation of topographic maps using Zeiss Stereoscopes with approximately 1:20,000 scale stereo-pair aerial images (the dominant method of producing orthophoto-derived topographic maps of rural areas of the United States from 1940-1993).

In 2002, the first regional LiDAR (Laser Light Detection and Ranging) aerial surveys of the Puget Lowland and Olympic Peninsula commenced, which allowed scientists and engineers to view the “bare earth” ground surface of those areas for the first time. LiDAR-derived digital elevation models (DEMs) with postings of 5 m or less provided an order-of-magnitude enhancement in discerning the topographic features characteristic of prehistoric landslide complexes, as shown in Figure 6, below. This figure is a shaded relief image of the North Fork of the Stillaguamish River Valley derived from a LiDAR aerial survey of the area in 2013. In USGS Open File Report 2014-1065, Dr. Ralph Haugerud annotated this shaded-relief image to highlight what he interpreted to be “older landslide deposits,” with those denoted by the letter “A” as the youngest in relative age, to ”D,” being the oldest (5).

We are not aware of any of these prehistoric landslides along the North Fork of The Stillaguamish River valley having been age-dated prior to the Oso Landslide of March 22, 2014.

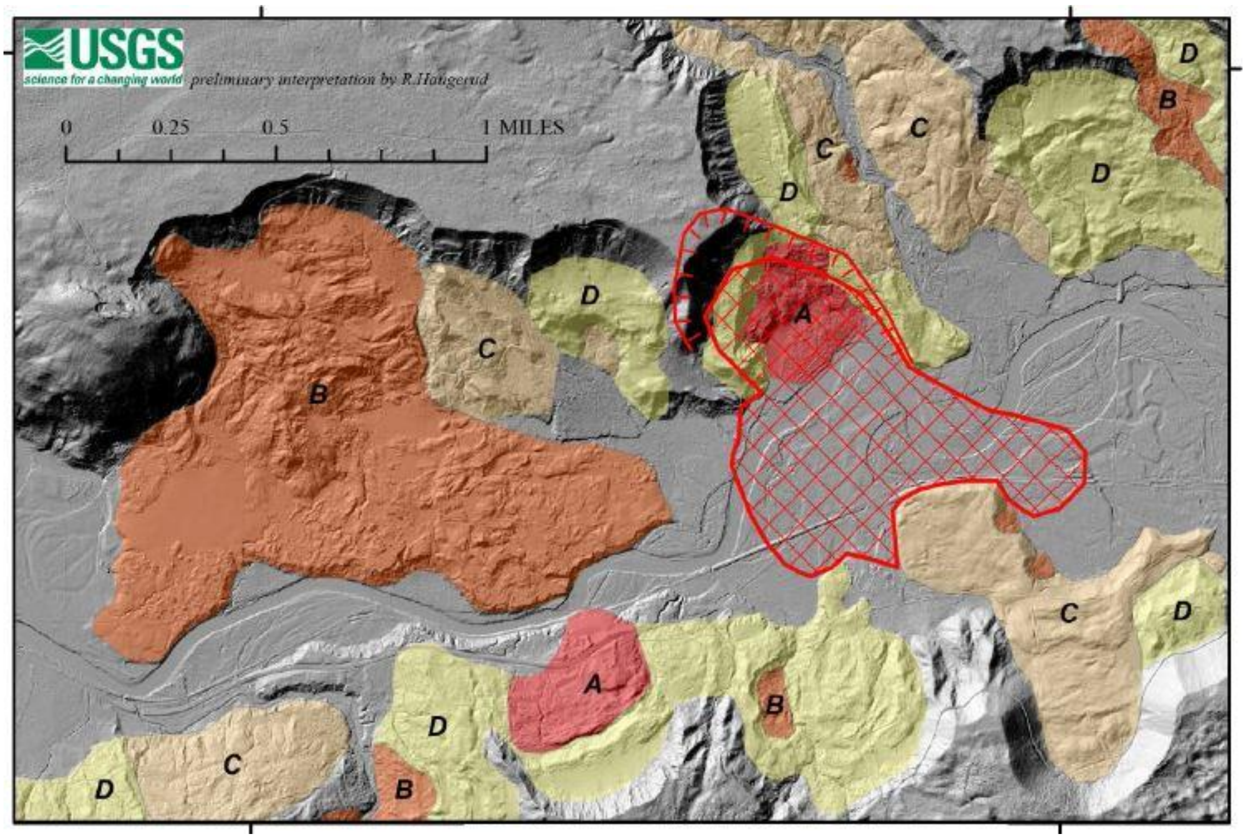

Figure 6: USGS-mapped historic and pre-historic slides (5).

Annotated shaded relief image taken from “Preliminary Interpretation of Pre-2014 landslide Deposits in the Vicinity of Oso, Washington,” by Ralph A. Haugerud, U.S. Geological Survey Open File Report 2014-1065, released after the March 2014 landslide (shown as red cross-hatch).

Historic Landslide Events

The site of the March 2005 Oso Landslide occurred where the North Fork of the Stillaguamish River makes its most severe turn northward, undercutting the erosion escarpment at the southeastern tip of the Whitman Bench. We have reviewed aerial images of the 2014 Oso Landslide area dating back to 1947. That review suggests that the slide gradually enlarged itself in the manner typical of retrogressive slumping with appurtenant toe flowage. The technical terms commonly used to describe various parts of a dormant or active landslide are presented in the block diagram below. The crown of the landslide is also referred to as the “main scarp,” “crown scarp,” or “head scarp.” The latter term is the one chosen herein. The term “surface of rupture” is synonymous with “slide plane,” basal rupture surface,” or “lystric rupture surface.”

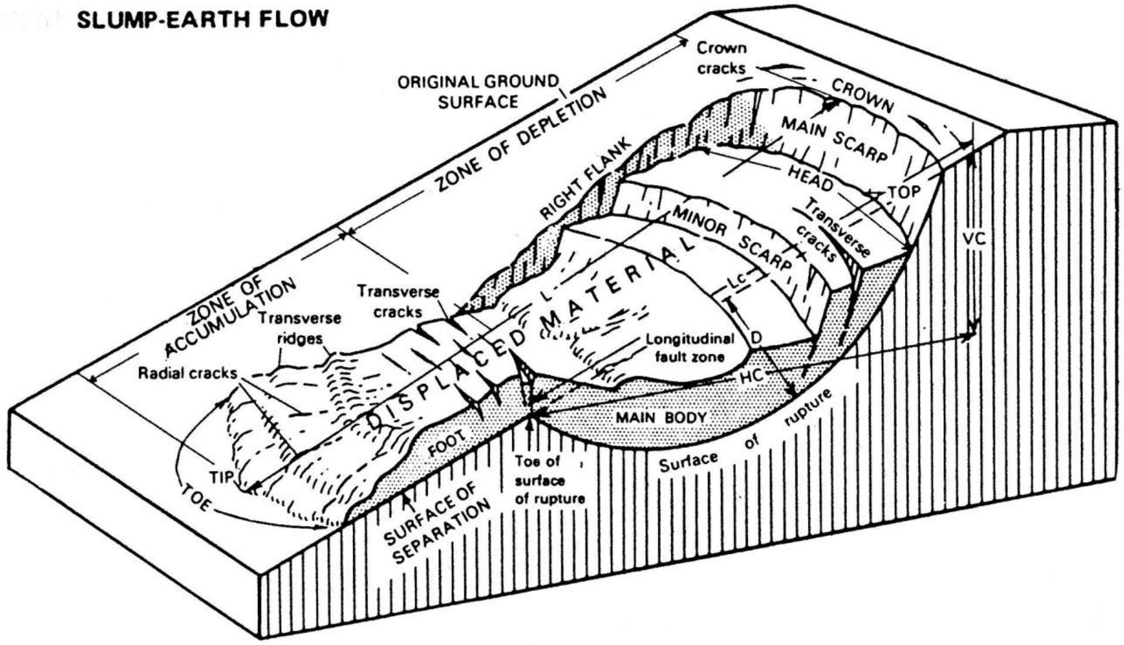

Figure 7: Block diagram of a rotational slump-flow style landslide (6).

Figure 7 is a block diagram of a rotational slump-flow style landslide, illustrating the technical terms commonly used to describe the physical aspects of landslides. This is from R.L. Schuster and R.J. Krizek, Eds., Landslides: Analysis and Control, Special Report 176 of the National Academy of Sciences in 1978 (6).

From 1952 through 2006 the head scarp of active landsliding exhibited a northeastward progression, towards the confluence of upper Headache Creek and the unnamed channel draining the head scarp graben of the Rollins Creek Landslide Complex. This headward erosion can be appreciated in Figure 8.

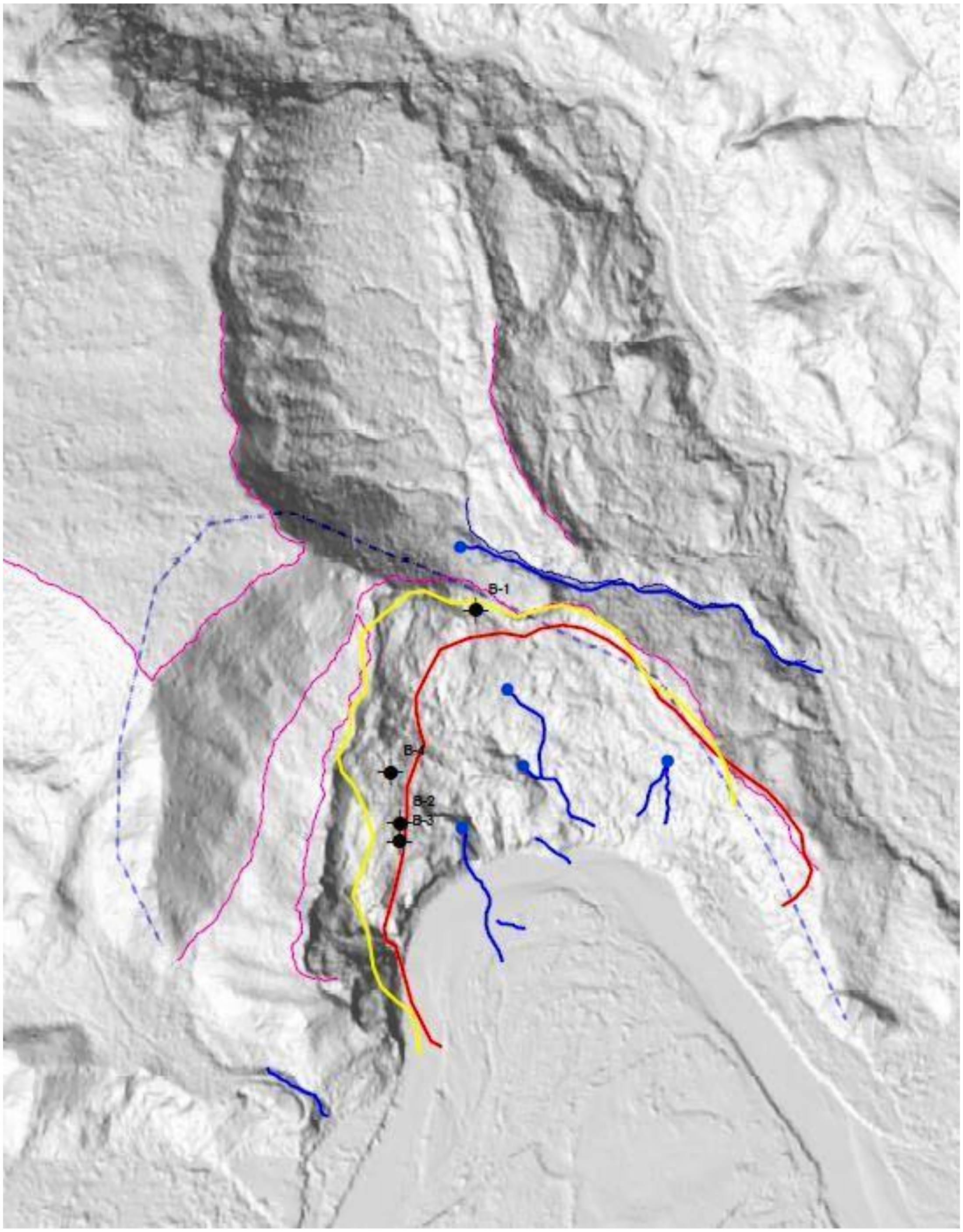

Figure 8: Headward progression from 1951 to 2014.

Historic head scarp regression of the Oso landslide overlain on the shaded relief map derived from the 2013 LiDAR dataset. The red line denotes the approximate position of the head scarp in 1952, as well as the four borings carried out at that time. Solid blue dots and lines denote perennial springs noted in 1952 and later. The yellow line denotes the approximate head scarp in 1969, and the magenta lines denote prominent scarp features in 2013, after the January 2006 slide. The dashed blue line is the USGS approximation of the March 2014 slide scarp.

During the interim 1947-2014 the river channel migrated significantly, into and away from the slope. This migration was most noticeable around 1969 and again, in early 2006. An aerial oblique photo taken in September 2002 (Figure 10) suggests that the basal slip surface at that time was well above the Olympia-age (33 ka) older alluvial unit exposed along the right channel bank, and that the basal rupture surface appears to be up in the lower fifth of the Vashon advance glacial lake deposits, comprised chiefly of over-consolidated clay and silt. Figure 9 is purported to show that the basal slip surface of the slide floored in the lacustrine clay above the exposed beds of pre-glacial Olympia beds seen here, forming the bluffs along the right bank of the river channel.

Figure 9: Aerial oblique image of the Oso Landslide by B. Tart (#4247), taken on September 9, 2002.

The January 2006 slide, shown in Figure 10 and Figure 11, appears to have involved more material than previous events. The toe of this slide also appears to have fluidized where the debris filled the river channel and displaced it southward, about 300 feet. Note the slope of the flowing toe, which is not flat, but gently sloping at what appears to be between 4 and 11 degrees (see Figure 11), not typical of liquefaction or lateral spreading. That fluidization was assumed to be something of an aberration at the time because of all the water absorbed by the debris entering the river. At that time, most geologists and geotechnical engineers in Washington also assumed that clayey landslides had little potential for liquefaction.

Figure 10: Aerial oblique view of January 2006 slide (7).

Figure 11: Slope of flowing toe from 2006 event (7).

Groundwater "Compartments"

From a preliminary assessment, there appear to be at least six "groundwater compartments," or hydrologic regimes, that may have impacted the 2014 Oso Landslide. The approximate areal extent of these is presented schematically on Figure 12.

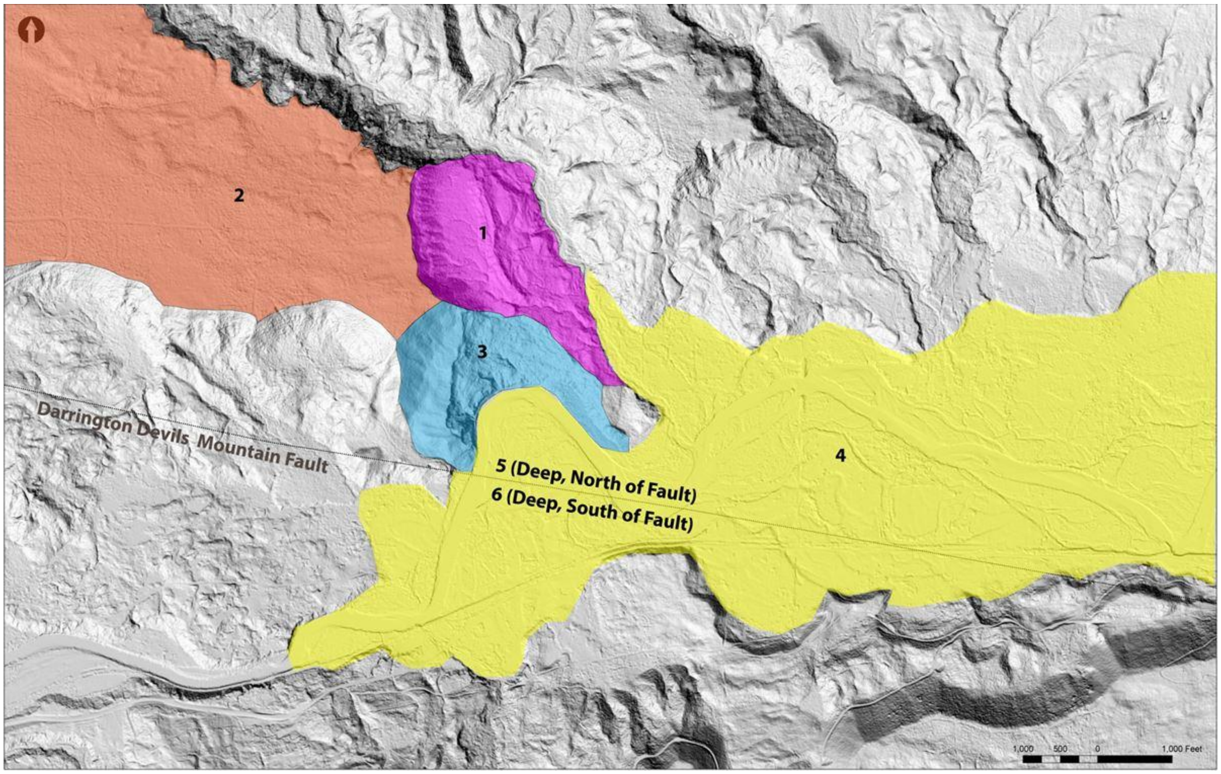

Figure 12: Groundwater 'compartments.'

Overlay of the shaded relief map derived from the 2003 LiDAR imagery. The six groundwater compartments shown here are briefly described below.

Groundwater compartment #1 delineates the approximate boundary of the well-developed head scarp graben of the Rollins Creek Landslide Complex, which drains into upper Headache Creek, just above the left flank lateral scarp of the Oso Landslide (compartment #3). Shallow groundwater trapped within the Rollins Creek Slide (likely on remnant blocks of the Vashon Till) may be preferentially directed towards the left lateral scarp of the Oso Slide. This is a sizable watershed which directs surface drainage towards the historic head scarps of the pre-2014 movements of the SR 530 Landslide. Shallow seepage tends to become “trapped” within old slide masses because of impervious stratigraphic units within the slide mass, or above basal rupture surfaces (commonly termed “slide planes”). These features are essentially small faults that usually form effective groundwater barriers, trapping moisture that infiltrates into the slide masses, the same way water is trapped in a bathtub. The upper portion of the Rollins Creek Landslide Complex drains in a southwesterly direction, joining the headwaters of Headache Creek. High soil moisture in this area may account for the increased volume of flowage evidenced along the left lateral scarp of the SR 530 Landslide, as well as during previous slide events (between 1952 and 2006).

Groundwater Compartment #2 is the Whitman Bench, north and northwest of the SR 530 Landslide. This is a depositional feature underlain by Vashon recessional outwash deposits, which are un-cemented, with an age of about 12,000 ybp. These materials appear to exhibit significant storativity, as gleaned from a visual inspection of the exposed head scarp, shown in Figure 13. This may be the easiest compartment to model, once we have some actual data gleaned from piezometers and rain gages positioned on the bench. The recessional outwash sands and gravels lie above lenses of Vashon recessional glacial lake deposits and the Vashon Till, which appears to serve as an effective aquaclude. Previous work appears to have assumed that the shallow flow within these sands and gravels is parallel to the existing platform surface, towards the prehistoric slide escarpment, above the SR 530 Landslide that periodically reactivated between 1952 and 2006. This assumption may or may not be true, it depends on the structure of the Vashon Till lying beneath the outwash gravels and sands. Geologically speaking, we would expect this till surface might actually dip upstream, towards the Rollins Creek Landslide Complex, to the east or southeast.

Figure 13: Head scarp evacuation scar of the March 22, 2014 Oso Landslide (8).

Figure 13 is an aerial oblique view of the head scarp evacuation scar of the March 22, 2014 SR 530 Landslide, taken two days after it occurred. A massive sequence of cohessionless gravels and sands were exposed, which rapidly receded over the following weeks. The Vashon Till is likely described by the dark lines of increased moisture and spotty seepage.

The Darrington-Devils Mountain fault likely forms a significant groundwater barrier in the area. In 2003 DGER geologist, Joe Dragovich (4) showed the fault striking northwesterly, out in front of the toe of the 2014 Oso Landslide, just north of the Steelhead Haven subdivision. This fault could serve as a significant groundwater flow barrier, along with the Advance Lake Deposits, which are also of relatively low permeability (hydraulic conductivity).

Groundwater Compartment #3 is the “trapped water” that falls as precipitation on, or percolates into, the disturbed ground of the prehistoric and historic Oso Landslide masses. This would be similar to the Rollins Slide Complex just to the east, and the Rowan Landslide Complex to the west, but occupying a much smaller area. Rainfall and some portion of the runoff and snow melt could be expected to infiltrate into the dilated slide mass, and is often trapped in tension cracks and grabens developed in the Advance Lake Deposits. The pre-2014 slide debris also appears to lie up-gradient of the Darrington-Devils Mountain fault, which could play some role in elevating pore water pressures on the uphill side of the fault.

The 4th groundwater compartment regimen would be the alluvial materials deposited by the North Fork of the Stillaguamish River, in Holocene time (last 6,000 to 11,000 years) age, river gravels, sands, buried tree trunks and limbs, miscellaneous organic debris, and other unconsolidated sediment, such as old landslide debris.

The 5th compartment would be the late-Pleistocene Olympia age glacio-fluvial sediments (denoted as “pre-glacial alluvium” in some well logs) beneath and adjacent to the Holocene river gravels, on both sides of the Darrington-Devils Mountain fault. On the north side of the fault, one might expect groundwater to be percolating southward (down-gradient from the Whitman Bench escarpment), trapped by the fault zone. In the area immediately up-gradient of the fault, we might expect abnormally high pore-water pressures to be developed, which could exert a significant impact on local slope stability (e.g. could even trigger large flow landslides).

The 6th groundwater compartment would be the late Pleistocene Olympia age glacio-fluvial sediments beneath the Holocene river gravels, on the south side of the Darrington-Devils Mountain fault, where groundwater pressures could be expected to be less than those that might develop north of the fault, in the area of the 2014 Oso Landslide.

Realistic estimates of groundwater flow require considerable effort and energy to formulate, unless previous workers in the area have already ascertained the physical characteristics of the various stratigraphic units, including their hydraulic conductivity (permeability) and transmissivity (rate of horizontal flow through an aquifer), etc. Within large landslide complexes, those figures can vary dramatically, depending on whether one sets monitoring wells in the upper portion (with active soil pressures) , the neutral axis (generating at-rest earth pressures), or the lower two-thirds of the slide mass (typically exerting passive earth pressures), as shown in the attached sketch. These figures are usually difficult to quantify without some reliable field data collected downhole, out in the field.

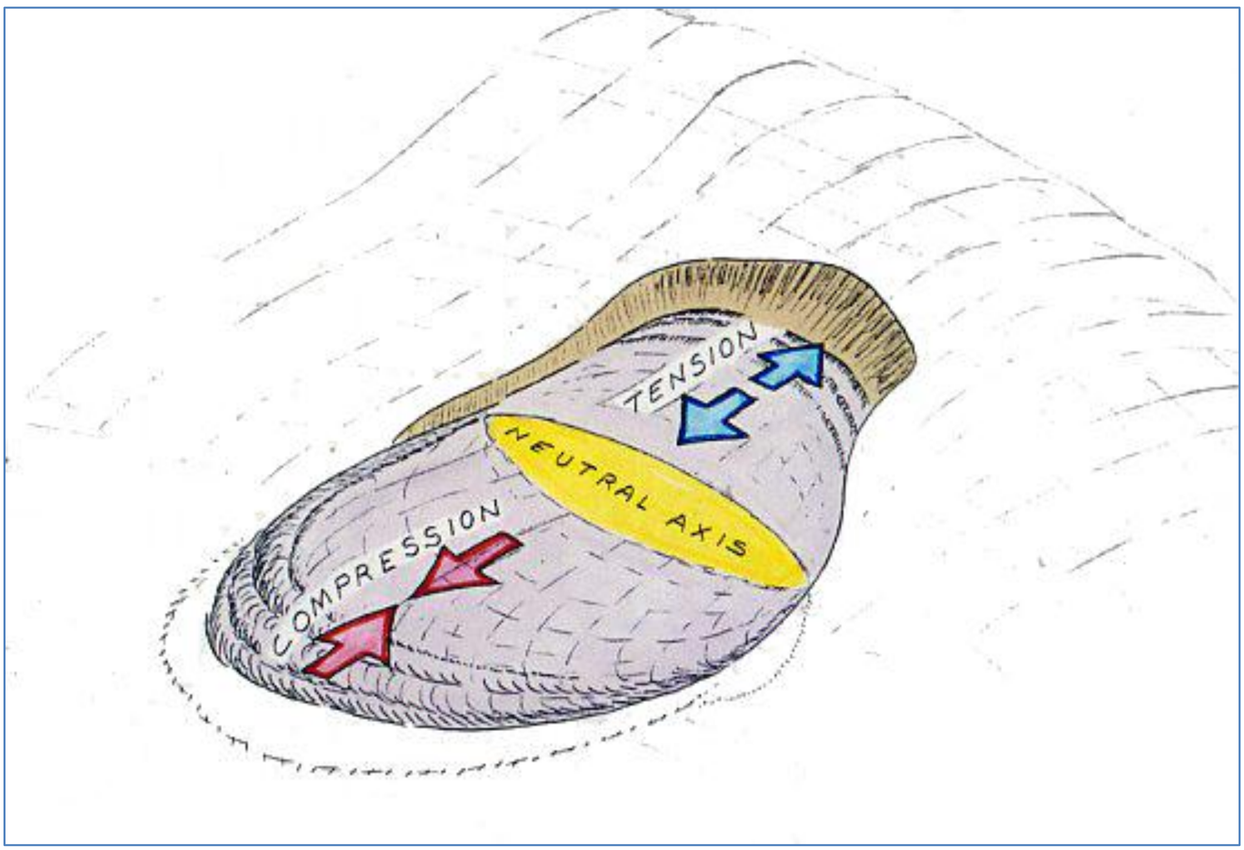

Figure 14: Common pressure states associated with active landslides.

Active, at-rest, and passive soil pressure states commonly associated with active landslides (Figure 14). The tensile stress regime in the upper third of a slide mass is typified by active dilation, with open fissures that readily absorb precipitation and surface runoff, which can hasten reactivation.

Seismic Signals

The SR 530 Landslide movements produced seismic signals that were recorded at seismological monitoring stations in the State of Washington and in the Province of British Columbia, Canada. The seismic signals captured by these seismological monitoring stations can provide insights into the failure mechanism of the SR 530 Landslide. The analysis of these low intensity seismic signals requires specialized expertise. Professor Douglas S. Dreger, Ph.D., of the Earth and Planetary Science Department at the University of California, Berkeley and Associate Director of the Berkeley Seismological Laboratory (http://eps.berkeley.edu/people/douglas-s-dreger), was asked to review the seismic signals that recorded the SR 530 Landslide movements and to review the papers prepared by Dr. Allstadt of the University of Washington (as presented in Iverson et al. (9), Allstadt (10) and by Drs. Hibert, Stark, and Ekstrom of the Lamont-Doherty Earth Observatory, Columbia University (as presented in Hibert et al., 2014 (11)).

Professor Dreger found that (12):

The mass movement of the SR 530 Landslide produced reactionary forces that excited low- and high-frequency seismic radiation. Hibert et al. (11) *and Iverson et al.* (9) *report on these motions and propose models of the force time history resulting from the slide based on the inversion of the seismic radiation. A published comment on the Hibert et al.* (11) *study by Allstadt* (10) *provides additional insight into the differences between the two studies.*

High-frequency (HF), 1-10 Hz, seismic records from nearby stations reveals two episodes of radiation approximately 4.5 minutes apart. The first episode of HF radiation is accompanied by contemporaneous low-frequency (LF), 0.01 to 0.03 Hz, motions that were inverted assuming time and position dependent single-force models ((11)*;* (9)*). Both studies filtered data to periods longer than 30 seconds (frequencies less than 0.033 Hz), and at these periods the wavelength of surface waves would be on the order of 30-100 km, significantly larger than the on-ground dimensions of the slide source and runout. At these long-periods the source is effectively a spatial point-source and the variations in signals to first-order would be sensitive to the force-time history of a point-source only with little to no spatial resolution. The method* *used by* (11) *parameterizes the force-time history using 8, 50% overlapping, 20 second triangles which results in a source model that is smooth compared to that of Iverson et al.* (9) *that allows for 2 second resolution in the parameterization of the force-time history. Both resulting models are similar in the estimated mass and the 90 second duration of the recovered force-time history, which is comparable to the 100-120 second duration inferred from the HF signals at the closest (11.7 km) station, JCW.*

However, the models differ substantially in detail. For the first episode of sliding the force-time history from Hibert et al. (11) *is a relatively simple function with an initial acceleration phase followed by a deceleration phase. They correlate their force-time history with the HF motions from JCW and find that the two overlap in time (*Figure 15*). The force-time history from Iverson et al.* (9) *is more complex, owing to the finer temporal parameterization of their model and involves two acceleration and deceleration phases. A primary conclusion in the Iverson et al.* (9) *paper from seismological analysis is that the "That high-speed, flowing motion of the landslide began after about 50 s of preliminary slope movement, and observational evidence supports the hypothesis that the high mobility of the landslide resulted from liquefaction of water-saturated sediment at its base." The delay in the high-speed motion is inferred from the apparent delay in HF motions at JCW with respect to the force-time history they obtained by inverting the LF signals at 18 broadband stations (*Figure 16*).*

Both studies make use of the nearest short-period station JCW to correlate with their LF force-time histories. In order to do this they must correct for propagation delays to the station. As illustrated in their respective figures reproduced in Figure 15 *and* Figure 16 *they obtain very different results. In Hilbert et al.* (11) *in their figure 5a, reproduced here as* Figure 15 *they show that while emergent the HF signal begins at the start of the LF force-time history. On the other hand,* Figure 16*, reproduced from Figure 5 of Iverson et al.* (9) *shows the HF radiation initiating approximately 50 seconds after the beginning of the LF force-time history. Iverson et al.* (9) *interpret this delay in the HF as being due to the slide moving initially as coherent, large masses, and then corresponding in time to their second LF acceleration phase it became more disrupted, incoherent, and rapid leading to the HF radiation. It is not clear why there should be such a difference in the relative timing of the JCW record with the respective LF force-time histories since both studies fit the long-period waves, in absolute time, for some stations in common, equally as well.*

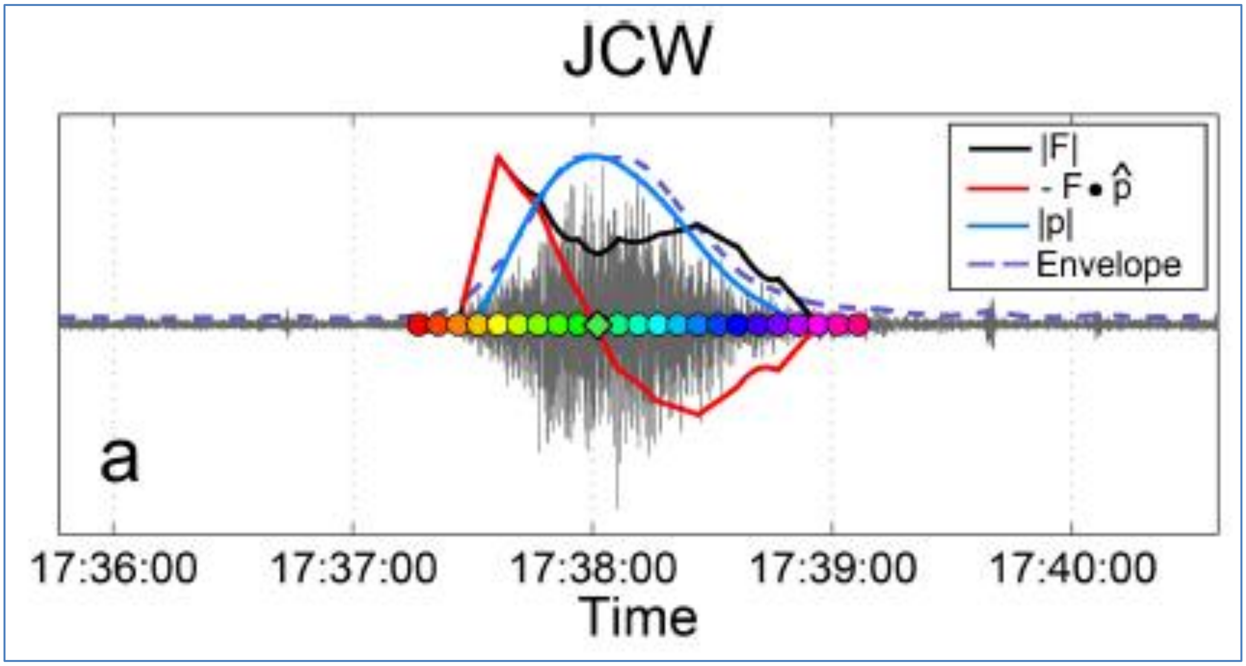

Figure 15: Comparison of HF (1-5 Hz) records at station JCW with the derived force-time history (red) from Figure 5 of Hibert et al. (2014). Absolute time in hour, minutes and seconds (UTC) is given.

In fact, it is not necessary to rely on the JCW record and perform the shifting to compare with the force-time histories. Transportable Array (TA) station B05D is located approximately 18 km from the slide, and is the next closest station. This instrument is broadband and therefore it is possible to directly compare the LF and HF signals. In Figure 17 *instrument corrected vertical component broadband records are compared with LF (0.01 to 0.033 Hz) and HF (1 to 10 Hz) signals in which a causal two-pole Butterworth filter was applied. The use of a causal filter is essential for investigating the onset timing of the two passbands. Both studies used the LF data at this station to constrain their force-time histories.* Figure 17 *shows that the onset of the HF radiation (dashed line) is nearly coincident with the LF radiation, and in fact appears to precede discernable LF signals. The arrows show LF pulses during the second phase of sliding as argued for by Iverson et al.* (9)*, and discussed later.* Figure 18 *expands on the first phase of sliding. Here it is evident that the records have emergent HF signals as much as 10 seconds prior to the onset of the LF signals that result from the acceleration of a significant mass of material. This observation is more consistent with the results and interpretation of Hibert et al.* (11).

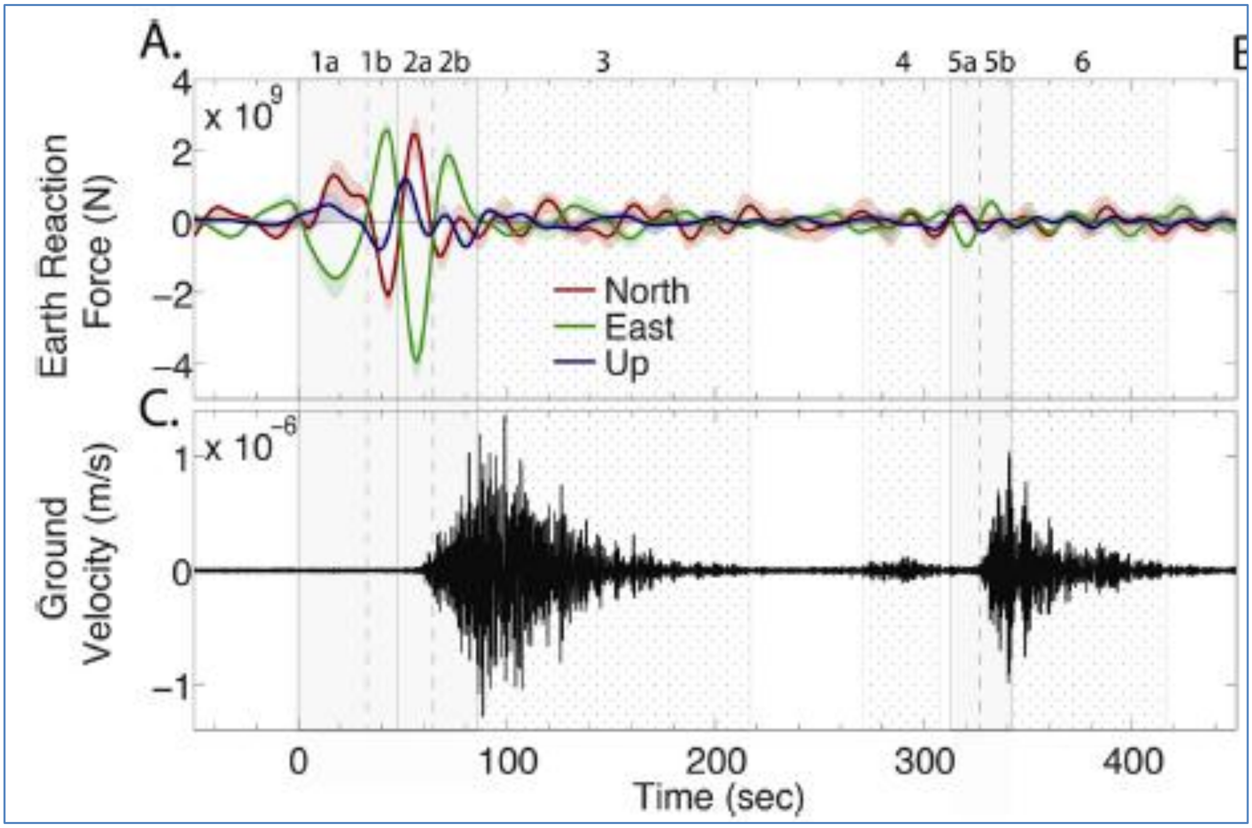

Figure 16: Comparison of HF (1-20 Hz) records at station JCW with the derived force-time histories from Figure 5 of Iverson et al. (2015). Time is in seconds from the onset of the force-time history.:

For the second phase of sliding, inferred from HF motions occurring approximately 4.5 minutes after the first, Iverson et al. (2015) find a relatively weak force-time history with near-vertically oriented forces that they attribute to a relatively small mass falling almost vertically at the scarp of the slide. Hibert et al. (2014) remark that HF bursts and more impulsive signals, as seen in the second episode of HF radiation can be indicative of fall of individual blocks or impacts of freely falling debris. There is a discrepancy in the interpretation of the mass of this second slide, where Hibert et al. (11) *places it at about 15-30% of the total based on energy estimates of the HF signal, and Iverson et al.* (9) *between 9-12% (from supplemental Table 1 of Iverson et al,* (9)*) based on modeling of weak LF signals. More analysis of the two approaches for estimating the mass of the second event is needed to determine* *which is correct..*

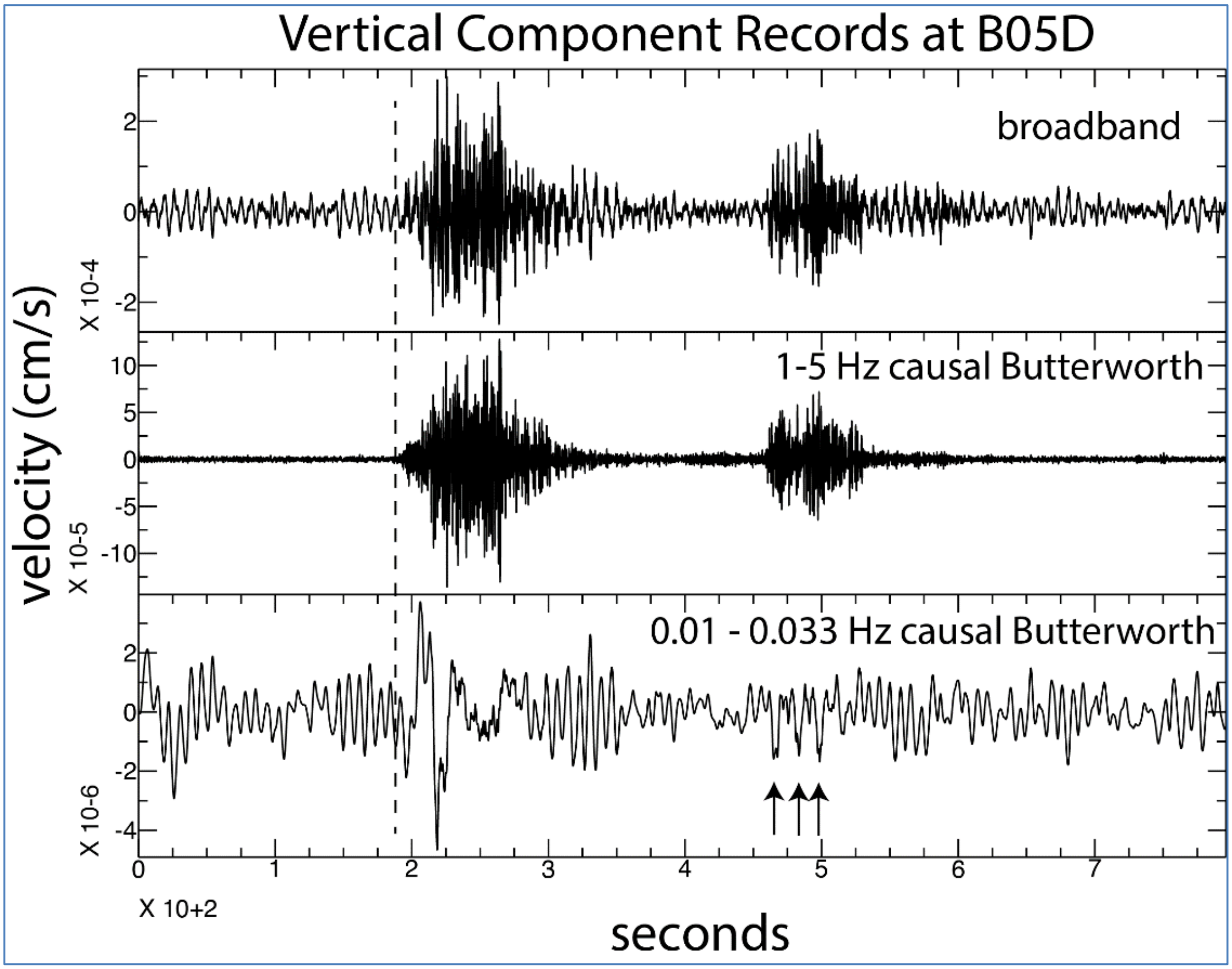

Figure 17: Comparison of vertical component records from the B05D station located 18 km from the slide. Broadband, HF (1-5 Hz), and LF (0.01 – 0.033 Hz) records are compared. Causal Butterworth filters were applied. The dashed line marks the onset of HF signals.

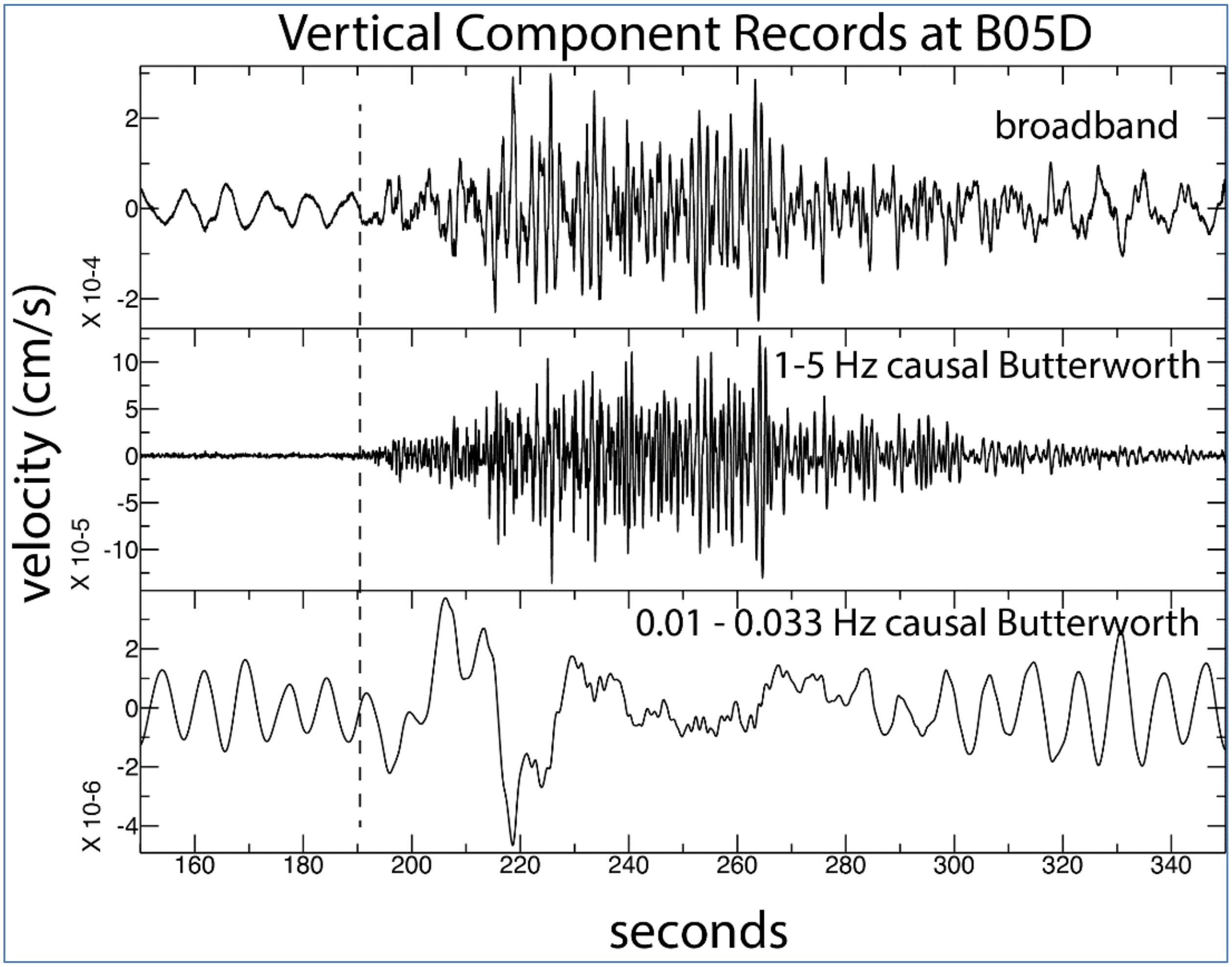

Figure 18: Comparison of vertical component records from the B05D station located 18 km from the slide. Broadband, HF (1-5 Hz), and LF (0.01 – 0.033 Hz) records are compared. Causal Butterworth filters were applied. The dashed line marks the onset of HF signals.

In summary, the complex dynamics of the SR 530 Landslide produced LF and HF motions that were well recorded by the TA and UW seismic networks. LF recordings enable the determination of estimates of the force-time history, which in turn can be used to deduce the mass of the sliding material. The two models in the peer-reviewed literature have many similarities in terms of the overall LF process such as mass of material, and duration of sliding. They differ in terms of the reported complexity of the force-time history. Iverson et al. (9) *present a more complex model with two periods of acceleration and deceleration in the first sliding event and they fit the data very well. However, the paper does not have sufficient detail to be able to evaluate whether these features are resolved by the data. To do so would require a comparison of the ability of a simpler single-force model such as used by Hibert et al.* (9) *to fit the same data so that the statistical significance of the improved fit afforded by the more complex model* *can be evaluated. Additionally, figures showing the contributions to the fit to the data separately from each of the acceleration/deceleration episodes in the Iverson et al.* (9) *model would be helpful in ascertaining the resolution of that complexity. It is not possible to compare the two published models in this way presently because they used different sets of data in their development. It does appear that for the stations in common, both models fit the data equally well. The two models differ by approximately 3.75 in peak force where the larger value is from Hibert et al.* (11)*. This difference is likely due to the use of multiple sub-sources in Iverson et al.* (9)*, and the fact they did not constrain their inversion so that the force-time history integrates to zero as theoretically anticipated, where Hibert et al.* (11) *did impose such a constraint. The two papers also differ significantly in their correlation of HF signals with their LF force-time models. Examination of the records from the nearest broadband station seem to suggest that the process began modestly indicated by low amplitude and emergent HF signals as much as 10 seconds before discernable LF motions are observed. The large amplitudes of the HF signal may correlate with the deceleration phase inferred from the LF B05D record approximately 30 seconds after the onset of HF motions (*Figure 17*). Additional work should be done to try to reconcile and understand the difference in the two studies to obtain greater understanding of the dynamics of the slide.*

Discussion of hypotheses to be tested

Plaintiffs have put forth a suite of theories and hypotheses, based primarily on previous studies.

Hypothesis 1 - Clear-cut timber harvesting will result in increased through-fall which results in a direct increase in groundwater

There is a lengthy empirical record in the literature regarding the amount of precipitation that reaches the ground (through-fall), and is therefore available to become groundwater under a coniferous forest and in a recent clear-cut harvest area. What this published empirical record does not do is show how much of the through-fall precipitation becomes part of a saturated groundwater zone and therefore increases pore water pressure in the subsurface soil and rock formation profile. The SR 530 Landslide area is particularly problematic from this perspective because, unlike many shallow forest soil cases, there are hundreds of feet of soil formations that water may have to travel through to reach the phreatic surface, and thereby create destabilizing pore water pressures in the ground. To understand the degree to which the timber harvest that occurred on the Whitman bench influenced pore water pressures in the ground below the bench, the soil layers must be characterized in depth and in plan, and the existing phreatic surface must be determined so that a reasonable reconstruction of what the surface might have been immediately prior to the landslide can be developed. While this work is not exacting, and will rely to some degree on professional interpretation of the subsurface conditions, drawing a conclusion in the absence of factual subsurface information is not appropriate.

It is also important to note that a common characteristic of sedimentary soil deposits which are what underlie the Whitman Bench is that horizontal hydraulic conductivity is much greater – easily by an order of magnitude – than vertical hydraulic conductivity. What this means is that water infiltrating downward in the subsurface profile will be distributed laterally to a significant degree. In the case of the timber harvest by Grandy Lakes on the Whitman bench, the small area of the harvest means that any increased infiltration will be distributed laterally reducing the impact to any destabilizing pore water pressures. Failure to consider the size of the harvest area and the common hydraulic conductivity characteristics of sedimentary soil deposits will no doubt result in an incorrect understanding of the impact of the timber harvest. Preliminary reviews of the precipitation infiltration portion of the work of Miller and Sias ((13), (14), (15)) is included in Appendices B and C, wherein the problems with modeling the precipitation/infiltration/evapotranspiration process are discussed. A preliminary review of the ID team report by Benda, et.al. (16) is attached as Appendix D, and provides discussion of the scope of work and applicability of the standard practice in assessing groundwater source areas at the time of its writing.

Hypothesis 2 – The SR 530 Landslide failure mechanism was driven by unconfined gravitational seepage

The first hypothesis that any geotechnical analyst is likely to employ when studying a natural deep-seated landslide is that the pore water pressure within and at the base of the slide mass was the result of unconfined gravitational seepage. While this is a common case, and is virtually insured with shallow landslides, deep-seated landslides such as the SR530 landslide can be subject to confined seepage at or near the base of the slide mass. Subsurface investigation followed by monitoring of pore water pressures is necessary to confirm or reject any hypothesis about seepage conditions.

Unfortunately, the monitoring of pore water pressures needs to include a minimum of one wet season cycle to be definitive. This is part of the necessary subsurface exploration and monitoring program that we have proposed.

It is also important to note that over-consolidated lacustrine clays which make up a significant proportion of the soil profile between the Whitman bench and the Stillaguamish river level can exhibit long term creep rupture behavior in which pore water pressures may only play a minor role. This type of soil response has been known for better than half a century, but because of the difficulty in analyzing it, has only recently been studied with sufficient detail to gain a mechanistic understanding. It cannot be discounted that a creep-rupture soil-response may have been a significant driver in the SR530 landslide. Laboratory tests and inconsistencies with alternate explanations will point toward this response at the SR530 site.

Hypothesis 3 – Erosion by the Stillaguamish river at the toe of the slope destabilized the slope and resulted in the SR530 landslide

In a natural landslide environment, steepening of the slope by erosion processes is always a consideration. In the SR530 landslide case, the contribution to instability from toe erosion by the river will be a function of the elevation of the basal shear surface of the slide mass. If the basal shear surface was above the river level, then the role of erosion by the river would likely have been far less than if the basal shear surface was at or below river level. This cannot be established by other than assumption without borings to identify the shear zone. Hence any comments about the role of erosion by the river are speculation. The subsurface exploration program that we have proposed should adequately determine the elevation of the basal shear surface so that the influence of toe erosion by the river can be appropriately considered.

Hypothesis 4 – Construction of settling ponds near the toe of the slope for the purpose of reducing sediment input to the river to benefit fisheries destabilized the slope

In a natural landslide, pore water pressures throughout the slide can play an important role in destabilizing a slope. Hence it is a reasonable hypothesis that higher than otherwise groundwater levels near the toe of the slide mass would have had a destabilizing influence. The sedimentation ponds near the river could have helped to sustain higher than otherwise groundwater levels near the ponds. The significance of this cannot be known without better subsurface information. It is also appropriate to point out that the toe area of the slope was made up of slide debris [a portion of the slide mass] from the 2006 Hazel landslide. It is reasonable to assume that this material which was sheared and remolded by the 2006 failure would not have been as large a factor in providing stability to the slope as it would have been if it was intact soil. This suggests that the influence of the ponds could have been relatively minor, but sustaining this hypothesis requires soil property and basal shear surface information that we expect to obtain from the proposed subsurface exploration and laboratory testing program.

Hypothesis 5 – Stability analysis performed before the SR 530 Landslide with subsurface information available at the time demonstrated within the standard of practice that the landslide was going to occur and endanger the Steelhead Haven neighborhood

There are two key points in understanding this hypothesis. First, there is an important difference between landslide hazard and landslide risk, and second, there is a range in objectives that are operative in studies that purport to assess landslide hazard or risk, and these objectives are associated with a range in the standard of practice that applies.

Landslide hazard (landslide susceptibility) refers to the possibility of landslide occurrence. Since landslide occurrence is assessed at the source or the origin area of a landslide, there may also be the hazard associated with landslide runout, which must be assessed differently than landslide occurrence because the mechanisms are different.

Landslide risk consists of the likelihood of landslide occurrence (i.e. 'failure') and the associated consequences of that 'failure' event which result in damage(s), the extreme of which is human injury or loss of life. Because landslides are discussed in the context of damage to personal property, such as fracturing a house foundation, risk is often considered synonymous with the likelihood of occurrence of the landslide. In these cases, human injury or loss of life is not usually an issue. For large displacement landslides, the consequences associated with landslide movement must consider a broader suite of consequences. In these cases, a separate analysis that includes consideration of public safety (i.e. loss of life) is necessary to establish the risks (likelihood of property damage, likelihood of loss of life, etc.) of runout which will vary depending on location with respect to the source of the landslide and the ground conditions between the source and the position of interest. In our experience, it is appropriate to say that runout assessment for a landslide (whether a shallow or deep-seated landslide) is largely based on the empirical record. This record is not of high resolution, and often includes an error term that is of the same order as the magnitude of the prediction. Recently (in the last 10 to 15 years), analytical approaches have been developed, but they are in their infancy, and generally have not been adequately validated or developed to the point of practical application as yet.

Miller (15) presents an estimate of runout based on a simple volume calculation that is in turn based on a series of models that we have reviewed (APPENDIX B - Review of Miller and Sias (1997, 1998) and APPENDIX D – Review of Benda et al. (1988)). This simple volume based estimate does not conform to either the empirically based approaches or mechanistic runout approaches that are currently in a state of development. As such, it is questionable that it can be considered meaningful. Since no empirical or mechanistic runout analysis appears to have been performed prior to the regulatory approval of the Grandy Lakes timber harvest, nor prior to the SR 530 Landslide, we will confine our remarks in this report about the standard of practice to the objective of assessing landslide hazard.

Scale is a very important parameter in assessing landslide hazard. We have included below (Figure 19), the Pacific-Northwest a sector of the map, “Landslide Overview Map of the Conterminous United States Legend” by Radbruch-Hall, et.al. (17). This map shows areas of landslide susceptibility based on the characteristic response of geologic formations and soils to natural or artificial cutting or loading of slopes, or to anomalously high precipitation. Note that the area around Oso, Washington is shown in base color which indicates low landslide incidence.

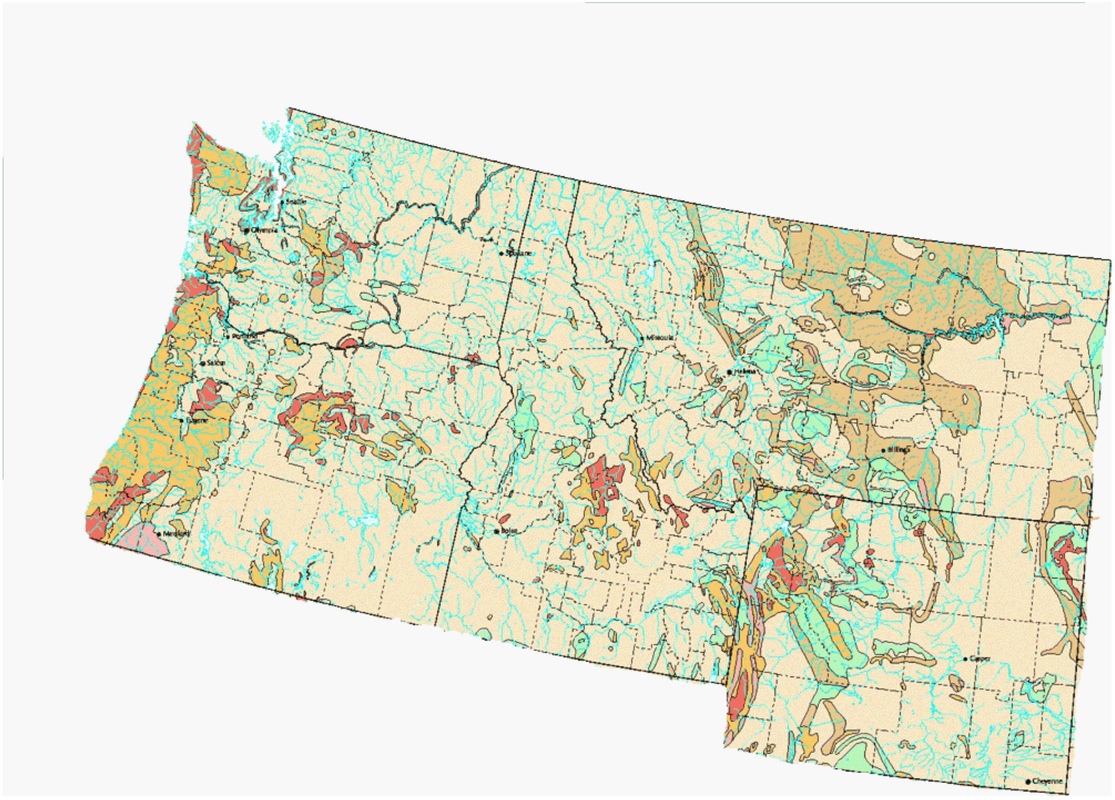

Figure 19: "Landslide Overview Map of the Conterminous United States Legend" (17).

How can this be correct? The answer is a combination of scale, the objectives of the work, and the historic record that was used to develop the map. Low incidence in this case indicates less than 1.5% of the land area is involved in landslides.

The map below (Figure 20) is specific to Washington, is at a larger scale than the Pacific North-West map above, and indicates with red dots the locations of reported landslides. The landslide record is often used as a first estimate of landslide hazard under the theory that areas that have a lot of landslides are areas of relatively high landslide hazard.

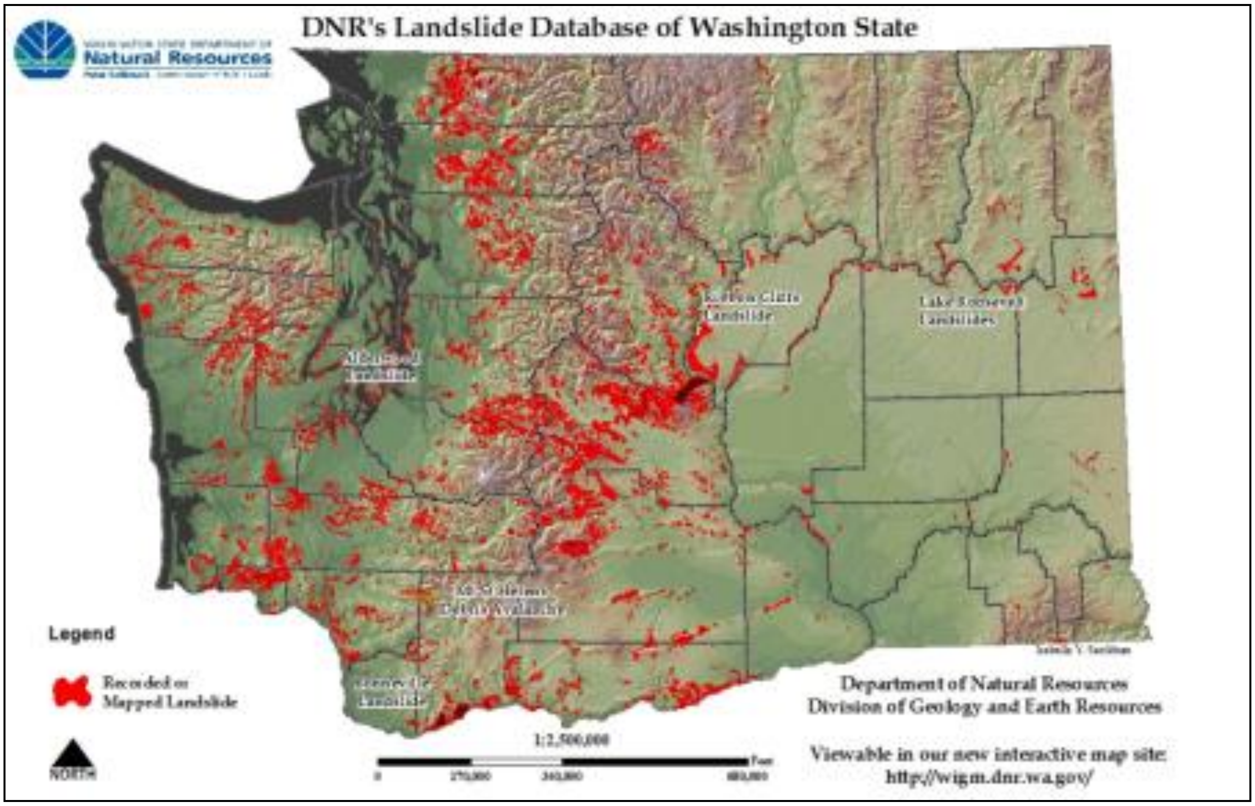

Figure 20: Locations of reported landslides in Washington State (18).

Greater detail can be seen in a map similar to that in Figure 20, but specific to Snohomish County which is shown below in Figure 21.

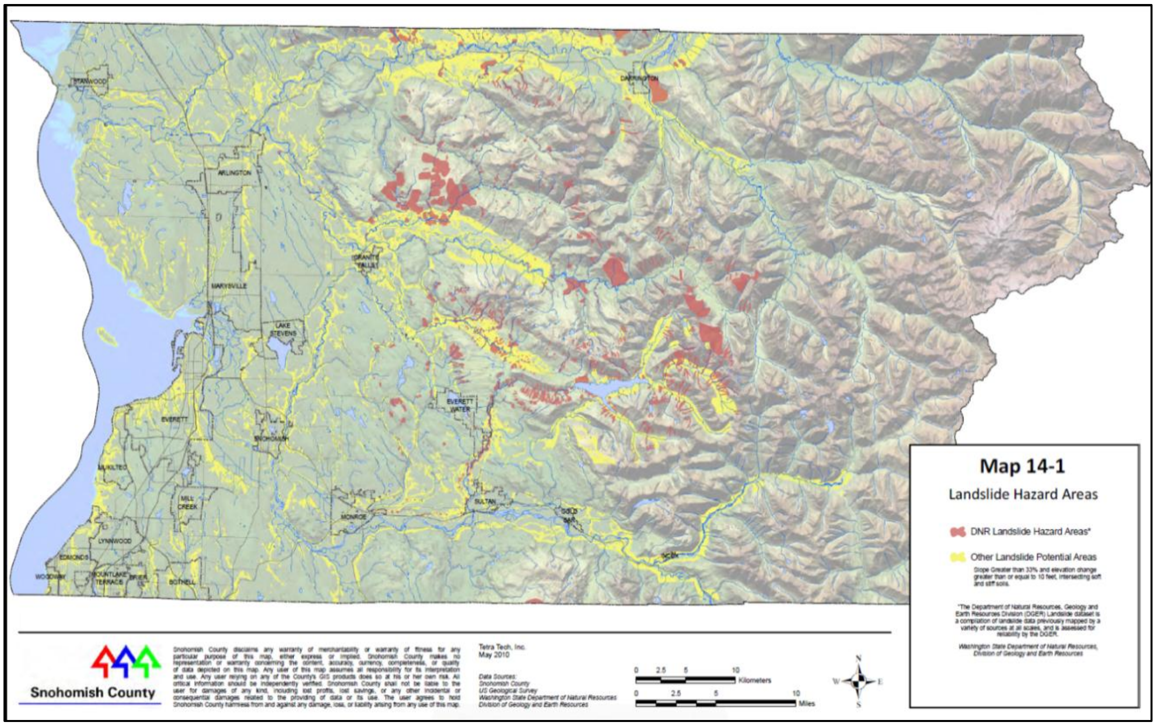

Figure 21: Landslide hazard areas in Snohomish County based on landslide data and topographic conditions (19).

And, finally we can move to a more detailed landslide map wherein the landslides features in the Stillaguamish river valley were mapped by professional geologists based on detailed LIDAR images (Figure 22). This figure includes the SR 530 Landslide site.

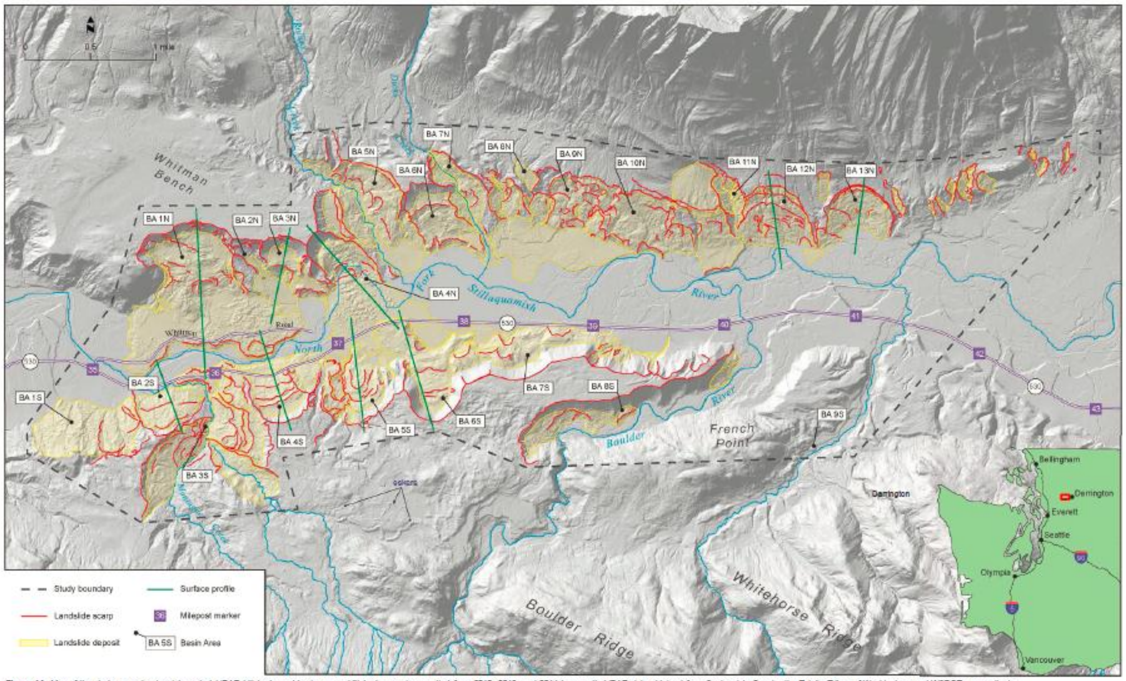

Figure 1A. Map of the study area showing interpreted LIDAR hillshade and basin areas. Hillshade mosaic compiled from 2010, 2013, and 2014 bare-earth LIDAR data obtained from Snohomish County, the Tulalip Tribes of Washington, and WSDOT, respectively.

Figure 22: Landslide features based on detailed LiDAR data (Gerstel and Badger, 2014).

The image above illustrates one of the problems with scale and the standard of practice in addressing landslide hazard. Virtually all of the Stillaguamish River Valley walls in the area of the SR 530 Landslide have the topographic features of landslides. If this is taken to indicate landslide hazard, then all of the Stillaguamish River Valley in this area [and beyond if the rest of the source report is consulted] is bounded by slopes that constitute a hazard. From the definition of hazard, and using evidence of prior slope movement as the indicator of hazard then all the slopes must be considered a hazard from the perspective of landslide origination.

Are there other means of establishing hazard? The answer is yes, but only through the addition of more detailed information about the slopes. That additional detail might be a better representation of topography, although the LIDAR image shown above, which has only recently become available, is about as detailed as topography gets. Additional detail would have to come from subsurface information. In general, subsurface information is so costly to obtain, that only inferences from surface information are generally available, and this comes in the form of geologic maps. Geologic maps will certainly take advantage of subsurface information from borings, tunnels, highway excavations, and mines or rock pits, when it is available, but such information will typically be very minimal for any given land area.

The standard of practice in landslide hazard mapping has been to employ qualified professionals for each step of the hazard mapping process. In general, it is not a quantitative process that is objective, but rather a qualitative process that is subjective.

There have been attempts to do quantitative hazard mapping, and in particular, the work of Miller (1995), and Miller and Sias (1997, 1998) are examples of that which apply to the SR 530 Landslide area. Various methods have been developed over the last 20 years or so, but to date, it is not apparent that any of these approaches have been adopted as being of sufficient value to warrant their use in either the policy or regulatory arena or for specific projects. To a large degree, the development of quantitative methods of landslide hazard mapping has lagged only slight behind the computing power of commonly available computers. However, increases in computing power were not matched by increases in the quantity or quality of site specific information on more than the topography of any land area of interest. Quite simply, it is well known that the occurrence of a landslide is a function of:

1. Topography [including modification of topography by nature and human processes].
2. Subsurface stratigraphy
3. Properties of the soils and rocks the lie below the ground surface [unit weight, strength parameters, saturated and unsaturated hydraulic conductivity]
4. The proximity and properties of geologic discontinuities to a particular site.
5. Precipitation [type and intensity over time]
6. The linkage of precipitation to groundwater seepage and the resulting pore water pressures in the soil and rock below ground surface
7. Seismic loading

Yet only topographic information has seen a quantity and quality increase over the last 20 years during which time various individuals and groups have been developing computer based quantitative landslide hazard mapping tools. The other variables are typically either ignored or assumed for the purpose of testing the model software. In some cases, model upon model is used for establishing all the parameters necessary for any particular landslide hazard mapping tool. While these modeling efforts are admirable computer exercises, to date, they have not produced usable information. Detailed reviews of Miller and Sias (1997, 1998) are presented in Appendices B and C for a more complete explanation of the deficiencies in that particular modeling effort.

Beyond hazard mapping or localized hazard determination, landslide risk assessment requires that the parameters listed above that have temporal variations be treated in a deterministic and probabilistic manner. Both deterministic and probabilistic analysis is necessary because the definition of risk includes the probability of damage at a particular location (e.g. a highway, a house, or where a person is located.). It is the location attribute that requires a deterministic assessment. This can be most easily understood by thinking about floods. Two houses that are side by side next to a river, but are at very different elevations will have different risks of being flooded simply because of the deterministic elevation. The lower elevation house might be flooded in a 1 in 25 year flood event on the river, where the higher elevation house would not be flooded until the river experienced a 1 in 100 year flood event. The same thing is true of landslide risk. The further that a house is located from a slope that has some hazard associated with it, the less likely that the house will be impacted.

The deterministic element of risk assessment is in its infancy. As in the case of hazard assessment, the first attempts at the deterministic component of risk are in the form of empirically based landslide runout distance or area graphs such as those presented by Iverson et.al. (2015) after the SR530 landslide, and shown below.

It is important to note that each plot has at least one logarithmic scale, and the scatter of the empirical runout data on the plot extends over one or more log cycles (9). This means that the variability in the empirical record is equal to or greater than an order of magnitude. A tool that is this variable is of little benefit in assessing risk.

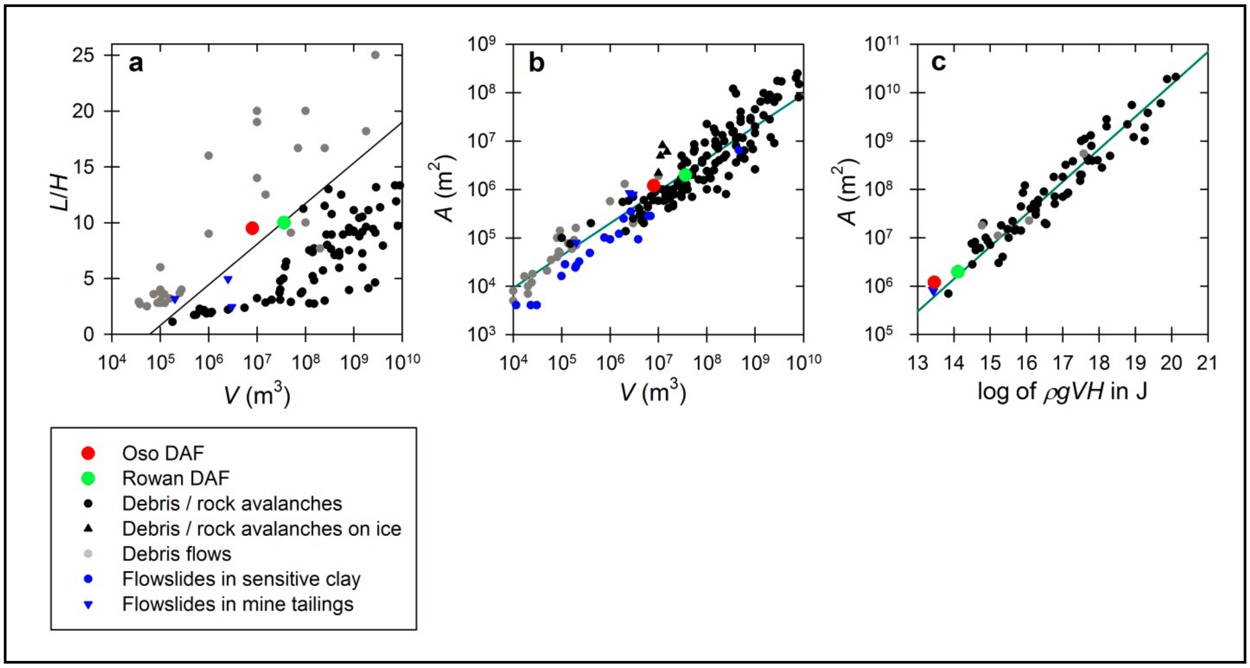

Figure 23: Logarithmic scale and scatter of data (9).

Proposed Field and Laboratory Program

Purpose and influence on slope stability analyses

It is not possible to evaluate the March 22, 2014 SR 530 Landslide and to form defensible opinions regarding its causative mechanisms and to identify potentially important contributing factors to its instability without subsurface investigations and monitoring that help define the landslide geometry, the engineering properties of the key geologic units, and the groundwater conditions within and below the landslide. For example, the prevalent starting point for a slope stability evaluation of a landslide is to perform conventional slope stability analyses of the pre-failure and post-failure landslide geometry. Established limit equilibrium methods used in slope stability analysis require definition of the problem: 1) geometry, 2) unit weight, 3) groundwater, and 4) strength to calculate a global slope stability factor of safety (FS) (e.g., Duncan and Wright (20)).

Regarding geometry (i.e., component 1 of the slope stability analysis), the surface topography is currently available through LiDAR surveys. However, the location of the basal sliding surface that defines the volume of the slide mass and identifies the soil unit(s) whose shear strength was simultaneously overcome that led to the landslide movement is not known. Thus, the calculation of a reliable factor of safety to describe the slope stability of the SR 530 Landslide mass is not possible without knowing where the basal sliding surface is located. The SR-530 basal sliding surface can be located through the advancement of several exploratory soil borings within the landside mass.

Regarding unit weight (i.e., component 2 of the slope stability analysis), the unit weights of the landslide materials can be estimated approximately using established correlations based on the information provided in previous and ongoing geotechnical studies (e.g., Shannon & Associates, 1952 (1); and Badger, 2015, personal communications regarding ongoing WSDOT Phase 1 Investigation of the SR-530 landside hazards (21)). The collection of soil samples through a drilling program performed within the landslide mass will help refine these estimates of unit weight. However, currently available unit weight information provides a reasonable basis for performing preliminary slope stability calculations.

Regarding groundwater (i.e., component 3 of the slope stability analysis), subsurface information within and below the landslide that would be used to characterize the hydrogeologic conditions of the SR 530 Landslide is not currently available. Two borings in the Whitman bench performed recently by WSDOT (21) do provide general information regarding the geologic units and the groundwater regime in that location of Whitman bench. This investigation needs to be supplemented with several soil exploratory borings with instrumentation (i.e., piezometers) within the landslide which would enable the analyst to define the groundwater conditions within the landslide. Definition of the hydrogeologic conditions is a fundamental input to conventional slope stability analysis methods.

Additionally, potential groundwater recharge areas that surround the SR 530 Landslide need to be explored to investigate their likely contribution to the groundwater within and below the landslide. To characterize properly the existing groundwater regime, for example, the contact between the overlying surficial sand/gravel unit and the underlying till unit that retards the transmission of water through it (i.e., it acts as an aquitard) needs to be located. Groundwater that moves down vertically within the fairly permeable sand/gravel unit would pool at the contact with the relatively impermeable till unit beneath it, and then this groundwater would move horizontally primarily through the sand/gravel unit roughly parallel to the surface of the sand/gravel unit and till unit contact. Thus, the elevation of the sand/gravel unit and till unit contact must be measured. It is also possible that significant layering within the surficial sand/gravel unit at Whitman bench would lead to localized transient perching of groundwater. This would cause lateral migration of groundwater above the sand/gravel unit and till contact. Packer percolation tests would be required at several levels within the surficial sand/gravel unit to investigate this issue. Only a relatively minor decrease in the permeability a soil layer within a unit is required to perch groundwater temporarily. Moreover, it is not just which areas of the ground surface that are connected to the subsurface groundwater that is important; it is also the timing of that connection. Hence, the field program must also include a complementary instrumentation and monitoring program that will enable one to observe the temporal response of that groundwater in relation to the observed precipitation through a minimum of one wet season. Lastly, with regard to characterizing the groundwater regime, the Headache creek area above a portion of the SR 530 Landslide may potentially supply the water observed in the numerous springs along the landslide's eastern side. This potential supply of groundwater to the landslide can only be assessed through a drilling program that defines the groundwater level within in the Headache creek area.

Regarding strength (i.e., component 4 of the slope stability analysis), it is crucial that the shear strength of the soil units that contain the failure surface that permitted the landslide movement be characterized. It is impossible to perform reliable slope stability analyses without a sound basis to estimate the shear strength of the key soil units that failed during the landslide movement. At this time, there are no reliable measurements of soil shear strength in the units within the landslide. Laboratory strength data for several of the intact soil units outside of the SR 530 Landslide may become available in the future through the ongoing WSDOT Phase 1 Investigation of the SR-530 landside hazards study (21). These data, when they become available, will be a useful complement to the strength data of the soil units that participated directly in the landslide.

It is possible that the lower part of the high plasticity, over-consolidated clay unit beneath the upper sand/gravel, till, and outwash sand units is the primary soil unit to be tested in terms of shear strength, because a deep-seated slide often forms a nearly horizontal basal sliding surface and such a surface would emerge near the location of the basal sliding surface of the 2006 Hazel landslide. Although this possibility needs to be confirmed through soil exploratory borings within the landslide mass, if it is confirmed, this unit would be a primary focus of the field sampling and laboratory testing program. Over-consolidated, high plasticity glacial clays are particularly susceptible to strength loss and could potentially help explain the cause of the rapid movement and length of the runout of the SR 530 Landslide. Fortunately, geotechnical engineers have developed a wide range of strength testing tools for developing reliable characterization of the shear strength of these types of materials. The stability assessment of the SR 530 Landslide is largely governed by the shear strength of the soil materials that failed during the SR 530 Landslide movement. Thus, strength data of the soil materials collected along the basal sliding surface within the SR 530 Landslide mass are required to perform reliable conventional slope stability analyses.

Moreover, the stress-strain responses of these soil materials are important as well, because several of the materials that are potentially involved in the landslide failure likely achieve their peak and residual strengths at different levels of deformation. Therefore, finite element numerical simulations with nonlinear, stress-dependent soil models that capture the differing stress-strain response of each key soil unit may be required, and the starting point for the stress-strain response of each key soil unit should be assessed. Thus, the stress-strain responses of the soils along the basal sliding surface and within the SR 530 Landslide mass are required as well as characterization of their initial state to perform reliable finite element simulations of the initiation and evolution of the SR 530 Landslide.

We know that at the instant before the SR 530 Landslide triggered, the part of the slide mass that moved initially had FS = 1.0. The possibility of multiple movement phases complicates the picture a great deal, however, for that initial mass, there are an unknown combination of slope stability component characterizations (e.g., geometry, unit weight, groundwater, and strength conditions) that can produce a FS = 1.0. The problem is currently ill defined. A sufficient number of these components must be discerned to a reasonable level of confidence to enable the slope stability analyses to be meaningful. The slope stability analyses are required to evaluate potential failure mechanisms and causative effects hypotheses.

Up until the day of the SR 530 Landslide, hydrogeologic assessments of the area surrounding the subject landslide have been based upon assumptions regarding subsurface geology and hydrologic conditions, and not upon actual subsurface data. In affixing the most probable reasons for causation, we seek to explore the general subsurface conditions, to ascertain whether the assumed conditions are even remotely commensurate with all of the various assumptions that have been proposed by various professional engineers and geologists, before and after the SR 530 Landslide of March 22, 2014.

Therefore, the subsurface geologic and hydrologic conditions need to be explored within portions of the March 22, 2014 SR 530 Landslide mass lying north of the North Fork of the Stillaguamish river channel, and within areas that may foster tributary underflow, towards the landslide, above and adjacent to its head scarp and lateral margins. The proposed program of subsurface exploration and monitoring will provide basic data that will enable reliable slope stability evaluations that are crucial to forming defensible opinions. Without these data, the results of conventional slope stability analyses are speculative. With the currently available data, which is severely limited in that no recent borings have been performed within the actual SR 530 Landslide mass, a large range of combinations of conditions could be assumed to calculate a slope stability FS = 1.0. This finding renders the results of such analyses as meaningless and of no assistance in discerning the cause and effects of the SR 530 Landslide.

Exploratory Borings

Exploratory borings are planned within the 2014 SR530 Landslide mass, on the Whitman Bench, and within the Headache Creek landslide head scarp to delineate stratigraphy and associated engineering parameters. Due to the disturbed condition of the slide mass following the March 22, 2014 event, it was not safe to deploy drilling equipment onto the moving slide mass to obtain subsurface data. Temporary access roads will need to be constructed for a number of the exploration locations so exploration equipment can access the target exploration locations.

Piezometers

Groundwater levels or piezometric levels in the case of confined aquifers, and the resulting pore water pressures are critical to any meaningful stability analysis. While an initial determination of groundwater conditions can be obtained within a few hours to a few days of drilling a boring and installation of peizometers, groundwater conditions are not static throughout the year. Critical levels will occur during the winter wet season, and may vary from wet season to wet season. Geotechnical specialists have forever had to contend with the uncertainty associated with year to year variations in groundwater conditions; it is neither reasonable nor possible to monitor groundwater for the length of time necessary for a statistically based understanding of the conditions. This said, it is very important, particularly with natural landslides that groundwater conditions be monitored through at least one winter wet season. This means that the exploratory boring program that we plan must be considered to extend through the winter of 2015-2016, with adequate time thereafter to reduce and analyze the results. The laws of nature require this time period.

Geophysical Surveys

Electrical Resistivity Tomography (ERT) is a passive non-intrusive geophysical subsurface exploration technique that can be used to determine the lateral and vertical changes in electrical resistivity of subsurface materials. These changes may result from variations in lithology and mineral content, pore water chemistry, and the presence of altered or water-bearing fractured rock. The method involves transmitting an electrical current into the ground between two current electrodes and measuring the voltage between two separate potential electrodes. The measured value at each point represents the apparent resistivity of the area beneath the electrodes. A combination of different electrode arrangements is commonly used to collect a sufficient number of measurements to produce a high resolution electric cross section representing the distribution of varying apparent resistivity values along the transect.

We believe that geophysical methods might be utilized on the Whitman Bench to ascertain the depth and geometry of the low permeability Vashon Till underlying the recessional outwash deposits. The depth of this contact appears to be about 125 to 150 feet beneath the ground surface. The ERT survey lines will need to be surveyed for precise elevation of the ground probes, in order to accurately gage the depths of buried horizons of contrasting properties.

The ERT method may be particularly suited to this site because the cap layer appears to be unsaturated, while the finer-grained till unit appears to be near saturation. The stronger the resistivity contrast is between the two materials, the easier it will be to make reliable interpretations of the collected data. ERT surveys of depths between 125 and 150 feet work best when carried out on crisscrossing grids, spaced 100 to 200 feet apart, with a few borings to confirm interpretations of the geophysical signatures.

Reservation

We reserve the right to clarify, amend and/or supplement our observations and forthcoming opinions based on development of additional information as this case proceeds. We reserve the right to provide rebuttal opinions at the appropriate time to expert opinions that may be disclosed by the Plaintiffs in this case.

Preliminary Report on behalf of Experts for State of Washington submitted on June 1, 2015 by:

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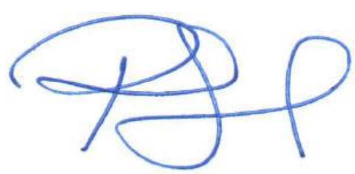
DR. MARVIN R. PYLES, Ph.D., P.E.

DR. JONATHAN D. BRAY, Ph.D., P.E., NAE

DR. ARNE SKAUGSET, Ph.D., RPF



DR. RUNE STORESUND, D.Eng., P.E., G.E.

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Appendix A – Aerial Image Catalog

Year Flown	Project Symbol	Scale	Type	Index Available	Required Photos	Prints Available	Scan of Available Prints	Diapositives Available	Negatives Available	Scan of Negative Available	Ortho Available	Digital Ortho Available
1947 1948	BBI	1:20,000	B/W	No	Unknown	3B-109 thru 113 4B-5 thru 7 6B-40 thru 42 7B-12 thru 15	Yes, Included	Yes	No	No	No	No
1956	CWD	1:20,000	B/W	No	Unknown	1R-119 thru 121 5R-41 thru 44 5R-46 thru 52	Yes, Included	No Yes	No	No	No	No
1962	SKAGIT 62	1:12,000	B/W	Yes, Included	41A-1 thru 4 42A-1 thru 4	No	No Prints Availible	No	Yes	No	No	No
1965	K-SN-65	1:12,000	B/W	Yes, Included	31-50 thru 55 32B-5 thru 9 33B-4 thru 9	Yes 5 thru 9	Yes, Included	No	Yes	No	No	No
1965	WFPA-65	1:60,000	B/W	Yes, Included	37-37 & 38 38-30 &31	Yes	Yes, Included	No	Yes	No	No	No
1970 1969	NW-69 NW-70 NW-69 NW-70 NW-69	1:12,000	B/W	Yes, Included	238-64B-19 thru 21 238-64B-22 238-64B-23 & 24 239-65B-18 & 19 239-65B-20 & 21 106-66C-7 thru 11	Yes 18 20 & 21 Yes	Yes, Included	No	Yes	No	No	No
1971	NW-H-71	1:63,360	B/W	Yes, Included	373-13B-28 thru 30 416-14B-4 thru 6	Yes	Yes, Included	No	Yes	No	No	No
1974	NWH-74 WASH-74	1:63,360	B/W	Yes, Included	7E-64 thru 66 8E-64 thru 66	64, 65 65	Yes, Included	Yes	Yes	No	Yes	No
1976	NW-C-76	1:24,000	COLOR	Yes, Included	32D-15 thru 17 33B-57 thru 60	Yes	Yes, Included	No	Yes	No	No	No
1978	TS-78-34-6E	1:24,000	B/W	No	Unknown	9-4 thru 7	Yes, Included	Yes	No	No	No	No
1978	NW-78	1:12,000	B/W	Yes, Included	77G-1 thru 5 78D-17 thru 21 79C-9 thru 13	1, 3, 5 20, 21 9, 11, 12, 13	Yes, Included	No	Yes	No	No	No
1980	NWP-80	1:12,000	B/W	Yes, Included	29A-1 thru 3 30A-1 thru 3 31A-11 thru 15	No 1, 2 13 thru 15	Yes, Included	No	Yes	No	No	No
1984 1983	NW-C-83	1:12,000	COLOR	Yes, Included	2-64-211 thru 215 2-65-185 thru 188 23-66-347 thru 352	Yes 186 thru 188 Yes	Yes, Included	No	Yes	No	No	No
1984	OS-84	1:63,360	B/W	No	3-7E-64 & 65 3-8E-64 & 65	Yes	Yes, Included	Yes	Yes	No	Yes	No
1987	NW87	1:12,000	B/W	Yes, Included	26-64-154 thru 157 29-64-43 thru 47 26-65-195 thru 197 13-65-136 thru 140 26-66-240 thru 245	Yes 43 thru 46 Yes 241 thru 245	Yes, Included	No	Yes	No	No	No
1988	WAC-88WA	1:32,000	B/W	No	Unknown	2-137 & 138	Yes, Included	Yes	No	No	No	No
1991	NW-H-91	1:63,360	B/W	No	3-7E-64 & 65 3-8E-64 & 65	64 Yes	Yes, Included	Yes	Yes	No	Yes	No
1991	NW91	1:12,000	B/W	Yes, Included	29-64-169 thru 173 21-64-61 & 62 29-65-182 thru 186 21-65-109 thru 111 32-66-190 thru 195	Yes	Yes, Included	No	Yes	No	No	No
1996	NW-96	1:12,000	B/W	Yes, Included	53-64-19 thru 23 53-65-45 thru 51 53-66-71 thru 76	Yes	Yes, Included	No	Yes	No	No	No
1998	NW-H-98	1:63,360	B/W	No	8-7-64 & 65 8-8-64 & 65	Yes	Yes, Included	Yes	Yes	No	Yes	Yes
2001	NW-C-01	1:12,000	COLOR	Yes, Included	27-64-30 thru 35 43-64-97 & 98 27-65-9 thru 13 43-65-146 & 147 43-66-199 thru 203	30 thru 32 Yes 9 thru 11 Yes	Yes, Included	No	Yes	31 thru 33 No 10 thru 12 No	No	No
2003	NWC-QT-03	1:32,000	COLOR	Yes, Included	161-55 thru 58 171-55 thru 58	No	No Prints Availible	No	Yes	Yes	No	Yes

APPENDIX B - Review of Miller and Sias (1997, 1998)

Review of "Deciphering large landslides: linking hydrological, groundwater and slope stability models through GIS", Daniel J. Miller and Joan Dias, Hydrologic Processes, Vol 12, pp 923-941 (1998).

Marvin Pyles, Ph.D., P.E.

Introduction

This article appears to be a "look what we did" article that is based on The Level 2 Watershed Analysis, Hazel, Washington, report done by Miller and Sias (1997) . I say this because, as near as I can tell, it contains more detail than the Hydrologic Processes article, but tracks exactly what the HP article includes. Therefore, this review will be based as much on the Level 2 Watershed Analysis report as it is on the HP article.

Overview

Both the Level 2 Analysis and the HP article describe in varying detail, a computer model based analysis of what was termed the Hazel landslide at the time. The computer analysis includes:

1. Assumed vegetation conditions ["We have no actual measurements at Hazel from which we can estimate vegetation parameters directly." P 2.2 Level 2 Report]
2. Meteorological data input to the analysis that was "inferred" from long-term climate observations at Darrington, Wa. Darrington precipitation and temperature records are daily values – turning this record into a six-hourly record was done with another model.
3. Simulated [modeled] interception loss, soil moisture status, stomatal resistance, and transpiration for an assumed forest and clearcut condition with an assumed well drained soil on a six hour time step.
4. Model [MODFE] computation of head at planimetric grid points over an area that covers portions of the Whitman bench, the slopes to the southwest, the slopes toward Rollins Creek, and the landslide area toward the Stillaguamish river. The Model was adapted from a USGS available two dimensional groundwater flow model that Miller modified for his use. The reports do not indicate that third party testing of the modified model was done at the time of

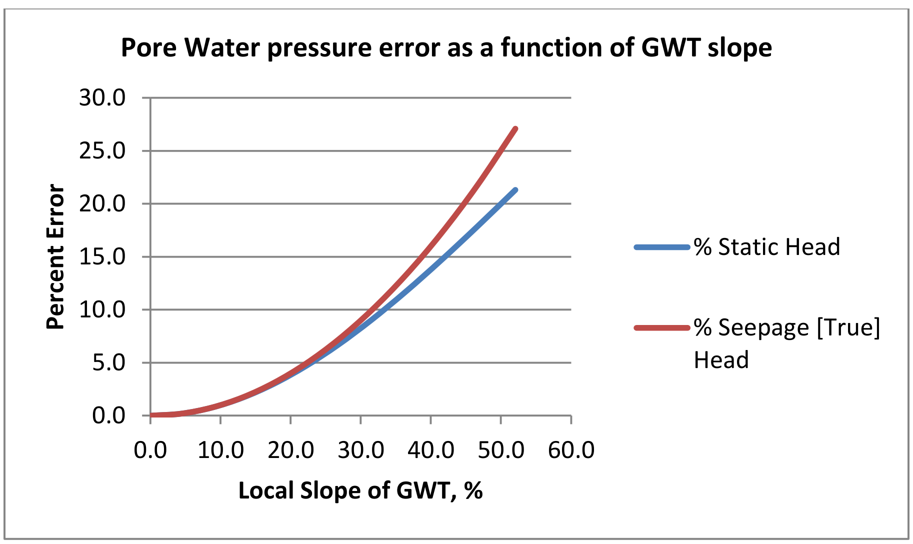
publication of Miller's work. ["The recharge area estimated here is obtained with and objective and repeatable model, but is based on limited field data. A true test of this prediction requires measurements of watertable elevations." P 3.4 Level 2 Report – the first sentence is not true since the modified form of MODFE was not presented for verification as a part of the report. The second sentence is true.]

Figure 3.2 in Miller's report illustrates the calculated groundwater recharge area to the SR530 Landslide [termed the Hazel landslide by Miller]. In the absence of modeling detail that would serve to verify the validity of the model results, it is important to note that the FEM modeled space is roughly rectangular trending in a northwest - southeast direction with an indentation at the boundary with the Stillaguamish river. The computed groundwater recharge areas also trend in this same direction. If the boundary conditions used at the southwest and northeast boundaries of the FEM modeled space do not match reality [which Miller admits is not known – see above] then this alignment of the recharge areas can be an artifact of the model, and not valid. Groundwater flow always seeks the path of least resistance. If the model [including boundary conditions] has been arranged so that the path of least resistance is toward the landslide area from the Whitman bench instead of from the Whitman bench to the nearest slope face, then Miller's calculated result with obtain. Since the only subsurface data available to Miller was from the Shannon report of 1952, some if not all of which was disturbed by sliding between 1952 and the late 1990's, there was no direct subsurface information to inform Miller's model analysis.

5. Reasonable computations of slope stability rely on correct groundwater conditions and correct subsurface information. Miller did not have on-site stratigraphy, nor did he have any groundwater measurements for the subsurface. He did have some interpreted stratigraphy and groundwater levels inferred from slope surface mapping in and around the air photo evident landslide feature as visible on air photos. The accuracy of this work was not verified, nor can it be. His efforts are certainly appropriate to inform a conceptual analysis for the purpose of demonstrating a potential method for analytically determining landslide hazard zones.
6. Stability calculations were done using Bishop's simplified method of slices. Detail explanation of the analysis and interpretation of the computed results were reported by

Miller in 1995. The 1995 paper indicates that both Bishop's method which applies to circular failure surfaces, and a planar failure surface were examined, but it is not clear that the planar case was included in the Level 2 analysis. The final result of the analysis is illustrated in Figure 3.4 of the Level 2 report. This figure shows a map of the slide area with stability indicated by colors that correspond to computed factor of safety within each 10m by 10m DEM cell. There are a number of problems with the analysis presented by Miller. The list below details some of the problems.

a. Pore water pressure computation error – Miller indicated that pore water pressure used in the analysis was computed from static head measured as the vertical distance between the GWT from the MODFE analysis and the base of each slice used in the stability analysis. Any time the GWT slopes, pore water pressures obtained thusly will be in error, with the true pore water pressure being less than computed. This results in a negative error [lower that true] in the computed factor of safety for the slide mass being considered. The pore water pressure error is shown in the figure below.



Since much of the ground slope in the slide area when Miller did his analysis, is in the neighborhood of 30%, an error of about 8% may exist which can produce a similar percent error in the factor of safety calculation. For some of the area, the ground slope is more like 50% which for an equal GWT slope can produce a factor of safety error of 20 to 25%. If seepage is exfiltrating from the slope face, the problem is complicated, but an error will still likely exist, albeit not as large.

b. The method of interpretation of factor of safety calculations presented by Miller was certainly new in 1995 when he first published it. Miller's publication was in Environmental and Engineering Geoscience, a publication of the Association of Environmental and Engineering Geologists and the Geological Society of America that does not generally represent the Quantitative Geomechanics or Geotechnical Engineering disciplines. Normally, publication in a refereed journal signifies a significant level of review and legitimacy. However, when the journal publishing the work is not a mainstream journal for the discipline, such legitimacy may be lacking. A literature search of publications since 1995 has not revealed adoption of the method. There are some very good reasons for this.

   i. Miller's 1995 analysis and the analysis in the Level 2 report is for deep seated landslides. While an exacting definition of "deep-seated" has not been standardized Miller specifically states that he excludes "shallow, saturation driven colluvial slides". It is also appropriate to define "deep-seated" as being beyond the influence of tree and other vegetation roots. Since the rooting depth of a Douglas-fir forest is typically 1 to 2 meters, depending on the soil conditions, and might be 3 meters as an upper limit, we might then infer that "deep-seated" can mean a landslide with a failure surface that is more than 3 meters below the ground surface at least at its deepest point. Miller's analysis in the level 2 report in effect does just this as a consequence of the DEM used. The grid spacing in the level 2 report is 10m, hence a circular failure surface defined between two adjacent DEM grid points is the smallest circular failure surface, and its radius would have an absolute minimum of 5 meters which places it below the rooting depth. There is little in common with a failure surface this size and the 2006 or the 2014 failures at the SR 530 Landslide site. The fact that failure surfaces this small, or nearing this size are considered is evident in Figure 4 of Miller and Sias (1998), and Figure 3.3 of the level 2 report. In both cases, a locally low factor of safety is shown that corresponds to a failure that extends for only 50 meters long the slope. This bears no relationship to the 2006 slide or the 2014 slide. Further, the two figures are for the same cross section through the hillslope, and yet they show different results. This suggests that Miller's work was still in a state of development at the time of one or both of the reports.

ii. The search method used by Miller to identify the potential failure surfaces with the lowest factors of safety includes calculations for both very small [5 meter radius] and very large [approaching a 400 meter radius] deep-seated landslides. When factor of safety for deep-seated landslides is represented on a 10m grid [figure 3.4 in the level 2 report], and there is no way to interpret from the grid what size of failure is associated with each cell value, it isn't possible to meaningfully understand the results in the context of concern over a 2006 or 2014 size slide event. If the majority of the low factors of safety represented on Figure 3.4 are for relatively small slide masses, then the level 2 report says nothing about the possible occurrence of a 2006 or 2014 size slide.

iii. Strength properties of the soils were assumed by Miller. In particular, Miller states on page 3.6 of the level 2 report that he used a simple average for the friction angle of the lacustrine clay, 23 degrees. He admits that the peak friction angle for a similar material from the literature is 35 degrees, and the residual friction angle is from 13.5 to 17.5 degrees. To quote Miller, "We have no other practical choice…". He goes on to indicate that his computed factors of safety are therefore overestimates for disturbed clay, and underestimates for intact clay. I agree with this, and it simply adds to the uncertainty about how to interpret his results. The impact of the difference between Miller's assumed average friction angle and the published values can be crudely illustrated by looking at the percent difference in the tangent function of the angles treating the intact and average residual friction angles as correct:

$$Potential\ \%\ Error = \frac{\tan(assumed\ fritcion\ angle) - \tan(correct\ friction\ angle)}{\tan(correct\ friction\ angle)} * 100\%$$

Correct Friction Angle, Deg	Miller's assumed Friction Angle, Deg	Percent error, %
35	23	-39
15.5	23	53

Assuming a single value of cohesion as Miller did will also produce errors with the same sign – a lower than correct values will produce a negative error term and a greater than correct value will produce a positive error. Cohesion can have a very large effect on the computed factor of safety because it is not affected in the same way as friction is by the trigonometric functions. Miller used a value of 14 kPa for the cohesion of the lacustrine clay, which is not an average of the published values that he references. The published values are 62.2 kPa for intact clay and zero for residual clay. The average of these values is 31.1 kPa, over twice the value the Miller used. Miller provides no explanation of this difference.

While Miller's use of an average did allow him to present a method of analysis for consideration, the error terms even as crudely represented above are simply too large for the results of the analysis to be considered as factual information to inform the a regulatory process.

iv. Following his base calculations of Factor of Safety, Miller presents a relative stability sensitivity as a way of examining the effect of changes in groundwater potential from presumed increased infiltration of precipitation and slope steepness as influenced by toe cutting by the Stillaguamish river. Such a relative stability sensitivity measure might be useful if it was based on correct stability computations to begin with, but sense Miller's computations cannot be correct, percent difference from an incorrect value is hardly a useful parameter to inform the regulatory process.

v. Stability analysis carried out by computer must be carefully monitored to ensure that there are not erroneous results that are an artifact of the way the automated processes programmed into the computer do the computations. The comment above about the size of the failure mass is one of these types of issues. If Miller used every possible cross section alignment for a two dimensional cross section analysis, and considered multiple failure surfaces as he indicates in his 1995 paper, then literally hundreds of thousands, perhaps millions of stability computations, were made when the time variable is included. It is a standard of practice in geotechnical engineering to conduct a series of confirmation computations on the “critical stability cases” as well as review the extent to which an automated process “considered” the potential failure cases. Miller does not indicate that this was done.

vi. There is another telling aspect of Miller’s work that confirms that he has prepared a concept paper, and not a true analysis of the SR530 landslide area. Beginning on page 3.12 of the Level 2 report, Miller discusses temporal patterns of slope stability. Review of figure 3.10, 3.11,and 3.12 will show that he differentiates factor of safety computations that vary over time from a high of 1.03 to a low of 0.98 due to changing model calculated groundwater conditions. Standard geotechnical engineering practice is to interpret computed factors of safety for slope stability to no better than one decimal place, and that is for the highest resolution stability studies where all properties and groundwater conditions are very well known. This means that none of Miller’s computed results showing temporal patterns is any different – all are within the accuracy of the best stability analysis methods. Again, Miller’s results cannot be consider appropriate for informing the regulatory process.

Summary Comments

The plaintiffs contend that Miller’s work that was reported in Hydrologic Processes in 1998 informed the DNR that the hillslope across the Stillaguamish river from the Steelhead Haven neighborhood was unstable, and therefore, regulatory approval of the timber harvest by Grandy Lakes should not have been granted. The review of Miller's work given above demonstrates that Millers' work fit the mold of a conceptual framework for analysis of potential zones of deep seated landslide hazard. Miller's work was not of sufficient specificity with regard to forest hydrology and geotechnical issues at the SR530 landslide site to be used in informing regulatory decisions.

APPENDIX C – Review of Miller & Sias Level 2 Watershed Analysis.

Review of "Environmental Factors Affecting the Hazel Landslide: Level 2 Watershed Analysis Hazel, Washington." Authors: Dan Miller and Joan Sias.

Arne E. Skaugset

This is a review of parts of the Level 2 Watershed Analysis that Dan Miller and Joan Sias produced on the Hazel Landslide. I was asked to review the parts of that document that pertained to the impact of timber harvest on the magnitude of groundwater recharge. That material is contained primarily in Chapter 2 of the document but I have read and reviewed portions of Chapter 1 also. Review comments are constrained to the topic of the impact of timber harvest on the amount of 'excess precipitation' that may be made available for addition to groundwater.

Timber harvest impacts the amount of 'excess precipitation' by changing the magnitude of losses due to evapotranspiration. In the report these changes are quantified using the Penman-Montieth evaporation model. As an evaporation model, the Penman-Montieth equation must be modified if it is used for transpiration or interception. For transpiration, an empirical aerodynamic resistance coefficient is used to restrict vapor loss due to the stomates in the plant leaves. For interception, the modification must account for when there is water on the vegetation. Thus, the model must be modified to deal with wet canopy evaporation, interception, or dry canopy evaporation, or transpiration. To accomplish this requires the development of a number of empirical coefficients to deal with the modifications.

The authors use the Rutter version of the Penman-Montieth evaporation model. This is an appropriate model and the Rutter version is its most contemporary formulation. The authors cite a publication that reports on the use of the Rutter version of the Penman-Montieth model to successfully predict interception and transpiration. However, realize that in the research described by that publication there was sufficient data of the type and intensity needed to allow the needed empirical coefficients to be estimated and to drive the model with all the needed parameters at the appropriate time step. This is the standard case of possessing a dataset of appropriate rigor, using half of the data to parameterize and calibrate the model and then run the model with the other half of the data. In these types of cases the models always function acceptably with close agreement between the predicted and observed values. This is the case that if you know the answer then with the appropriate model you can predict the answer.

A problem with Millar and Sias Level 2 analysis is, of course, that they did not have a comparable dataset of similar rigor available to them on site. The data set did not come from the Hazel site but from Darrington and only maximum and minimum daily temperature and daily rainfall were available. All the other needed inputs for the model and the information needed to develop the empirical coefficients had to be synthesized. So the problem with the modeling exercise is not the applicability of the model but the quality and applicability of the available data. The final product can only be as good as the data.

Perhaps the single most egregious aspect of the document with regard to the impact of timber harvest is the gratuitous use of the words 'groundwater recharge' to refer to what is, in the general vocabulary of hydrology, called 'effective precipitation' or 'precipitation excess.' Precipitation excess is defined as the difference between gross precipitation and the sum of all losses due to evapotranspiration. This is the same definition that the authors use for 'groundwater recharge.' In other words, the authors, perhaps intentionally, infer in a subliminal way that all precipitation that occurs in excess of losses due to evapotranspiration is instantaneously added to groundwater. The fact that precipitation excess is labelled groundwater recharge throughout the document appears intentional. The authors state on page 2.3, 2nd paragraph that . . ."it was considered unnecessary to model . . .time dependent redistribution of moisture within the root zone." Also, "We assumed that additions to groundwater occurred with no attenuation of moisture draining from the root zone." In other words, any precipitation in excess of evapotranspiration instantly becomes groundwater without any attenuation in space and/or in time. This statement is made in spite of fact that the authors clearly understand the geology of the site. In Figure 1.3 the authors show a definition sketch that shows a deposit of 'Outwash Sand' that is several times, perhaps as much as ten times, thicker than the rooting zone of the soil. Yet despite their seeming understanding of the nature of the site they assume that precipitation makes it from the ground surface to groundwater without consideration of storage in the deposit along the way or without recognition of a residence time in transit. To me, this is the single most egregious shortcoming of the document and renders moot the findings regarding the impact of changes in hydrology due to timber harvest.

The authors parameterize their model for high, intermediate, and low recharge cases and choose estimates of model parameters accordingly. This results in a range of values for excess precipitation (recharge) for the forested case; high 923 mm (36.3 in), medium 708 mm (27.9 in) and low 512 mm (20.2 in). The mean annual precipitation (MAP) for the Hazel site is reported to be 1685 mm (66.3 in). If the precipitation excess is reported as percent runoff (% RO) instead of recharge the values are; high 55 percent, medium 42 percent, and low 30 percent. The only value of these three that is reasonable and agrees with experimental watershed results is the high value of 55 percent. In fact, even that value is low. On average the expected value of precipitation excess or runoff is about 65 percent. It appears in the forested condition the authors drastically overestimate ETs in the medium and low case.

The authors go on to calculate the difference in recharge (precipitation excess) between a forested condition and a clear cut for the three cases. These results are; high 281 mm (11 in), medium 665 mm (26.2 in), and low 863 mm (34 in). Again, the values associated with the medium and low recharge cases are an overestimate when compared to experimental data. The authors even report these data in Table III. The highest reported water yield increase is 615 mm (24 in) and the rest of the reported values are much less than that. Further, the study that produced the 615 mm increases (Needle Branch, Alsea Watershed Study) is an extreme case with treatments that could never be replicated in contemporary times. Thus, the other results (increases of 12 to 18 in) are much more realistic. These results are in line with the high recharge case, which means the other two cases drastically overestimate the impact of timber harvest on precipitation excess.

Why is this? Why are the model results not in better agreement with the paired watershed study experimental results? There are perhaps two reasons: summer interception and winter transpiration.
Let's consider summer interception first. Summer interception does exist and I think the way it was calculated was, most likely, reasonably correct. The error comes in assigning the difference in forest and clearcut summer interception directly to groundwater recharge. The difference in excess precipitation due to differences in summer interception between a forest and a clearcut will go into the soil, where it will be stored in the soil in the root zone and be used by summer transpiration. The idea that during the summer transpiration season excess precipitation will go to groundwater recharge and not to satisfy transpiration defies credulity. None of the calculated differences in summer interception should be included in groundwater recharge. These values are, in fact, excess precipitation but they should not be considered groundwater recharge.

Secondly let's consider winter transpiration. There is no doubt that real winter conditions can be entered in the Penman-Montieth equation such that a vapor pressure deficit occurs across the forest/atmospheric interface and transpiration can be calculated. But that doesn't mean that it occurred. There are numerous situations that exist when there is a favorable vapor pressure gradient across the forest/atmospheric interface but transpiration doesn't occur. During the night is one such time, the stomates close. Also, the summer season when the plant goes into moisture stress, the stomates close. Winter appears to be one of those times. There is no research that shows that transpiration, as in sap actually moving in the tree, occurs during the winter. Even if it did exist, the Penman-Montieth equation without some grounding in the physiology of trees, would overestimate it. Thus, winter transpiration is overestimated and helps lead to overestimation of actual ETs.

The gratuitous use of the words 'groundwater recharge' and the erroneous addition of summer interception and winter transpiration to groundwater recharge cause most of the findings from the document to be moot. The effect of timber harvest on water yield or excess precipitation is pretty well known and can be estimated quite accurately with empirical equations and concepts. The results from the empirical case studies are not replicated, at all, by the model results in this document. But, while the excess precipitation can be calculated easily and more accurately by other methods that still doesn't mean that it should be instantaneously added to groundwater, in space and time. That aspect of the problem still requires refinement.

APPENDIX D – Review of Benda et al. (1988)

Review of: Lee Benda, Gerald Thorsen, and Steve Bernath, October 30, 1988 [revised 11/23/88], Report of the I.D. Team investigation of the Hazel Landslide on the North Fork of the Stillaguamish River (FPA 19-09420).

Marvin Pyles, Ph.D., P.E.

- The introduction indicates that the driver for the investigation was concern for salmonids in the Stillaguamish River. This is consistent with the primary considerations of the time.
- The discussion of the mechanism of landsliding at the Hazel site attributes groundwater as the most important condition causing slope failure. This is clearly a professional judgment, which depending on the temporal context is reasonable. This said, the conclusion is not substantiated with any quantitative analysis. A lack of quantitative analysis is consistent with the scope of work in the investigation. [p. 2].
- The report suggests that mudflows, which are listed as one mechanism of failure that has been occurring are most damaging because of their potential for long runout. No scale is provided for the meaning of "long runout". Cited observation of Shannon and Associates (1952), was that a mudflow had partially dam the river in December of 1951, suggesting a scale for "long runout" to be somewhat less than the width of the river. Cited observation of Thorsen (1969) was that in 1969, a recent caving of the scarp of the 1967 slide had occurred resulting in a mudflow several hundred feet long. Since the scarp in 1969 was well over 1000 feet from the river, it can reasonably be inferred that Thorsen's observation for mudflow runout was that it didn't reach the river, or if it did, it did not cross the river. The Benda et al. report does indicate that in 1967 a mudflow dammed the river for 4 hours, but there is no reference for this information.
- It is not reasonable to conclude from the report statement about long runout that it included potential impact to the Steelhead Haven residential area.
- The report states that the upper limit of the slide scarp was at elevation 600 feet. The elevation of the Whitman bench is approximately 890 feet, which means that Benda's investigation was of slope stability that did not encompass the entire slope up and including the Whitman bench. Hence his perspective on slope stability does not share a common context with the SR 530 Landslide.

- The section of the report on “Groundwater Sources of the Hazel Landslide” states at the outset [the first sentence] that there are “two primary groundwater source areas” which supply springs within the landslide. Benda defines a groundwater source area as the surface area located above an aquifer.
    1. There is no description of what field or other work was done during the two field visits that allowed the two groundwater source areas to be determined.
    2. The description of area 1 states, “The groundwater-source area has formed as a result of outwash sand deposits overlying a relatively impermeable glacial deposit containing clays.” There is no statement as to why the source area that Benda shows in Figure 1 of the report does not extend further to the north on the Whitman bench, all of which fits quoted description.
    3. There is a curious juxtaposition proposed in the description of area 1. The report states that it is a primary source of water to Headache creek, but that it doesn’t supply springs in the eastern portion of the slide. The problem with this is that the eastern portion of the slide is between much of the source area and headache creek. There was a topographic high on the slope between the western portion of the slide and Headache creek, but this would only be a visible barrier to surface water, not groundwater.
    4. Groundwater source area 2 as indicated by the report includes part of the Whitman bench above the Headache Creek drainage to the east, and the slopes of the Headache Creek basin above and to the west of south trending Headache Creek. Again, there is no justification for terminating the source area where the boundary is shown on the Whitman bench.
    5. The report makes definitive statements such as, “This aquifer supplies groundwater to the springs which emerge at the eastern edge of the slide mass.” It is not possible to determine such a relationship from merely waking the surface of the ground and observing where there are springs. The location of a spring is often controlled by geologic discontinuities which may not be apparent from the ground surface.
    6. Most if not all of the report statements that define the boundaries of the inferred groundwater source areas are reasonable hypotheses [contradictory statements excepted] that cannot be well tested without some form of subsurface investigation.
    7. The last statement in the groundwater section does explain the context of the Benda report and therefore the scope of any inferences that should reasonably be made from

the report. The report states, “The resulting springs are responsible for past and present mudflow activity.” In other words, it can be inferred that surface water from springs was saturating soil downslope to such a degree that a mudflow could occur. Given the location of the springs that the report discusses, the context is mudflows from the lower portions of the slope below the Whitman bench, and not a mudflow resulting from a SR 530 Landslide size event.

- The section of the report on groundwater response to timber harvesting is taken directly from the literature as opposed to factual data pertinent to the SR 530 Landslide area. Is the application of the literature appropriate to the SR 530 area? Yes and no. The reduction in evapotraspriation (ET) from the literature can reasonably applied to the site with one exception. The 16 to 27 year time period stated from the literature does not simply turn on and then turn off at the beginning and end of the period. For a well reforested clearcut area, reestablishment of forest ET would occur steadily over the period of re-growth until the leaf area index matched the prior forest stand.
    1. There is a contradiction in the final paragraph of this section that illustrates the degree to which the material is taken out of the literature without necessarily making sure that it applies.
        - Note this sentence: “Increases of soil moisture by reducing evapotranspiration are more likely to increase seasonal water tables and less likely to affect groundwater tables during major storms.”
        - Note this sentence at the end of the section: “… increased groundwater due to removal of forest cover increases the likelihood of landsliding because the magnitude and hence the recurrence interval of the storms that contribute to failure would be decreased.”
        - These statements are somewhat contradictory. The first statement is broadly true, but the latter statement can be reasonable applied without quantification only to shallow landslides, which is not the concern with the SR 30 Landslide area.
- Report Conclusions
    1. Triggering mechanism and groundwater areas:
        - The conclusion that groundwater is the triggering mechanism is reasonable, but has not been established with subsurface information and quantitative analysis.

- There is no explanation other than visual observations of springs on the hillslope as a basis for the groundwater source areas.

2. Effect of Timber harvest in the groundwater recharge areas:
   - On a unit area basis, the increase in groundwater [combination of saturated and unsaturated groundwater] can reasonably be expected to be in the range given the first year after harvest, but it would steady decrease over time as forest re-growth occurs.
   - The statement, "The exact amount of destabilization is not known nor is it possible to predict the monthly or season precipitation necessary to result in failure with or without timber harvest." Is exactly true.
3. Timing of slide activity and timber harvest:
   - The report uses a 10 to 15 year time window following harvesting when landsliding was observed as confirmation of the association between the harvesting related groundwater increases and slope failure. The problem is that at 15 years, the pre-harvest ET is likely to be 75% or more recovered. Equal rainfall in years 1 through 15 following harvest would have had to produce failure for this relationship to be correct and single valued [groundwater being the sole cause].
   - No serious examination of the precipitation record was done, and this would be necessary to confirm the hypothesis.
4. There is no conclusion with regard to the potential for risk to human life.

Comments: The Benda, et.al. report reasonably represents the standard of practice at the time. In-depth subsurface exploration and geotechnical characterization of either a site of the soil and rock materials was not the standard. Hence the report was an accepted level of investigation at the time. The conclusions cannot be expected except by happenstance to be correct in retrospect. Contradictions pointed out in this review would have been common in similar investigation reports for other areas. The net effect of this type of FPA approval element is that on the average forest management impacts on landsliding would be reduced, but at any given site, the inaccuracies in characterization of the site would not precluded slope failure.